Alternating Current Motors

OPERATION, CONNECTION, MAINTENANCE

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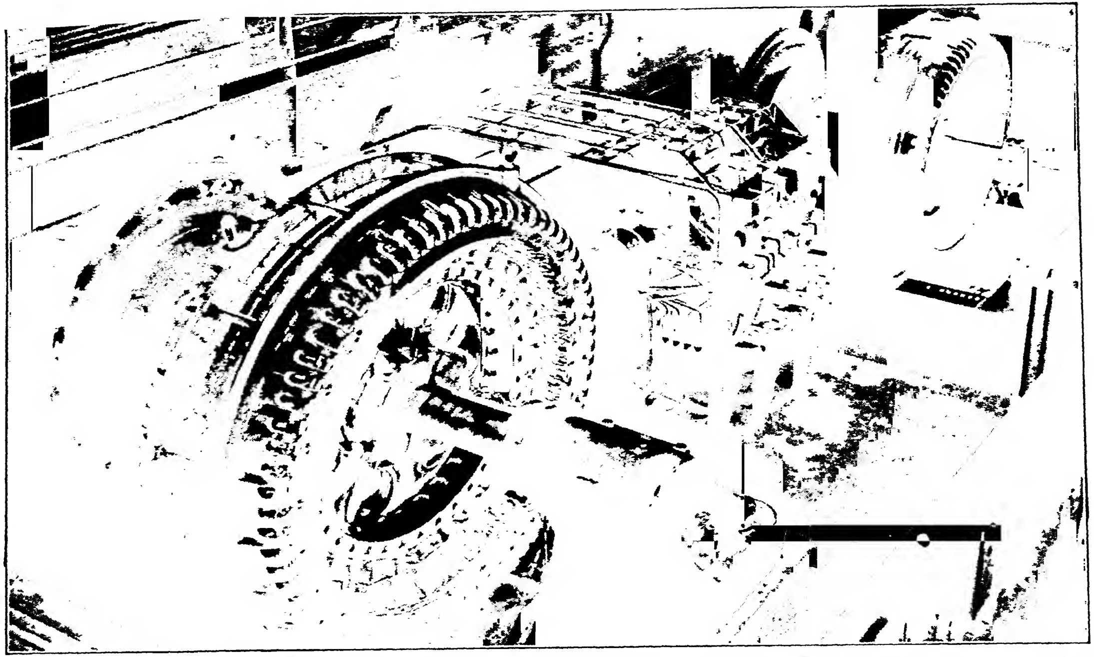

MULTIPLE INSTALLATION OF 500-HORSEPOWER, LOW-SPEED SYNCHRONOUS MOTORS IN A FLOUR MILL, EACH DRIVING A SEPARATE LINE SHAFT THROUGH A MAGNETIC CLUTCH

Courtesy of Fairbanks-Morse Company, Chicago

ALTERNATING CURRENT MOTORS

OPERATION, CONNECTION, AND MAINTENANCE

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PREFACE

OF prime importance in the study of technical subjects is the fundamental theory upon which such subjects are based. The study of theory isolated from its application can become pointless and uninteresting. For this reason this text presents the theory of alternating-current motors in conjunction with the practical aspects of their construction, operation, and maintenance.

An alternating-current motor cannot operate without the electric current produced by an alternating-current generator; and since the same electrical and magnetic principles apply to both motors and generators, the second chapter in this text discusses the types of alternating-current generators and their operation.

It is also necessary to acquaint the reader with the various types of motors. There are two major classes of motors, single-phase and three-phase motors. The single phase classification includes the universal, repulsion-induction, repulsion-start induction-run, and the capacitor types. In the three-phase group are the squirrel-cage, wound-rotor, and the synchronous types. The thorough explanation of principles of operation and construction along with the helpful illustrations enable the reader to acquire a complete understanding of the various types of alternating-current motors.

A motor without a capable operator is like a train without an engineer—of little value. With this in mind the authors have made every effort to incorporate into the section on the operation of generators and motors all the facts necessary to keep a motor operating satisfactorily. The operator is told first how to select the proper motor for each particular application; then he is told how to maintain it in good running order. Also included in this chapter is the important knowledge of power-factor correction.

Since universal motors are operated on either alternating or direct current, they may develop troubles that are specific to this type. The six-page chart in this section enables the cause to be located quickly and the proper remedy applied.

The repulsion-induction type of motor has been built in large numbers chiefly by two manufacturers, and each uses a different type of centrifugal-operated short-circuiting device and brush-shifting arrangement. Special operating instructions and a listing of the troubles common to each of these two types have been prepared for the reader.

The stator winding is the source of much of the trouble that occurs in polyphase induction motors. In some cases the defective coils may be cut out of service by simple repair. The author discusses when this can be done and when it is necessary to rewind the entire stator. The many special hints or kinks that are so valuable to experienced repairmen are revealed for the benefit of the new operator. A table is included listing the symptoms, causes, and remedies of common troubles of polyphase induction motors. The importance of this section of the text cannot be overestimated.

Our largest alternating-current motors are usually synchronous motors. The size and complexity of these motors make a special set of operating instructions necessary. All operators running synchronous motors will value this chapter of the book highly.

Each type of motor has its particular type of starter and controller. With the use of schematic diagrams and various illustrations the reader becomes acquainted with common types of starters and controllers.

For all aspects of alternating-current motor, construction, operation, and maintenance, the reader will find this text a helpful guide.

THE AUTHORS

The text material of this book also appears in the cyclopedia "Applied Electricity"

REMOVING STATOR COILS FROM A 10,000 KVA GENERATOR THESE COILS WILL BE REPLACED BY NEW ONES WITH BETTER INSULATION

Courtesy of Westinghouse Electric Corporation

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SOLDERING THE CONNECTION OF ONE COIL TO ANOTHER ON A LARGE ALTERNATING-CURRENT MOTOR
Courtesy of Electric Machinery Mfg Company, Minneapolis, Minn

TYPES OF ALTERNATING-CURRENT MOTORS

Two or more magnetic fields are always required in either direct- or alternating-current motors to produce torque. These fields set up magnetic poles which act upon each other through attraction or repulsion to produce the rotating forces called torque. The construction of the machines for utilizing direct current are quite different as a rule from those using alternating current to produce these magnetic forces.

The stationary field and revolving armature, with most of the line current passing through brushes to the moving element, is almost universally used with direct-current motors. The alternating-current motor has practically the reverse arrangement, as this machine nearly always has the main line current passing through stationary windings. This current passing through these windings sets up a revolving field which acts on the rotating element in various ways with different types of motors to produce torque. How this is accomplished in the various types of alternating-current motors will be explained in the discussion of each. The important points of difference to bear in mind are these. The direct-current motor has stationary poles and a revolving armature, while the alternating-current motor has stationary coils with rotating field flux. The stationary part of a direct-current motor is called *the field* and the moving element *the armature.* The stationary part of the alternating-current motor is called *the stator* and the moving element of the motor is called *the rotor.*

SPEED OF ALTERNATING-CURRENT MOTORS

The speed of a direct-current motor can be easily changed by raising or lowering the applied voltage or using resistance in either the armature or the field circuit, wide ranges of speeds being obtainable with the direct-current motor through this means. Only very limited speed ranges are possible with alternating-current motors. One of the elements producing torque in the alternating-

current machine is the revolving field. No rotor of an induction motor can revolve faster than this field rotates. The top speed of a motor on an alternating-current circuit then becomes the synchronous speed of this revolving field. More about this fact will be discussed under each type of motor.

The speed of this rotating field is determined by the number of poles and the rapidity with which these change from north to south. The frequency which is determined by the number of changes of polarity in the poles depends upon the number of cycles per second obtained from the alternator supplying power to the circuit. A 2-pole motor connected to a 60-cycle source would have 60-pole changes each second for each pole which would make 3600 changes per minute. Therefore, the stator field would rotate at a synchronous speed of 3600 and would limit the rotor speed to a like amount. If the stator was wound with four poles instead of two, the rotor would advance only one-half a turn for each cycle of change; hence, two cycles would be required on the stator to turn the rotor one complete revolution. Thus with a 4-pole stator the rotor speed would be 1800 revolutions per minute or one-half what it was with a 2-pole stator. A stator wound with six poles would require three complete cycles or pole changes to make one complete turn of the rotor. Mathematically the synchronous speed of a rotor would be

$$\text{r.p.m.} = \frac{\text{cycles} \times 60 \times 2}{\text{number of poles}}$$

Sixty is used because there are 60 seconds in a minute and two must be used because it requires a pair of poles, one for each half cycle, to make the magnetic circuit. If the frequency was changed from 60 to 40, the speed at which the poles would change polarity would shift the same amount. A 60-cycle motor on a 40-cycle circuit would run at only two-thirds its former speed. Note—this is not a practical thing to do but is used merely for illustration. A motor under these conditions would run hot because of lack of iron in the magnetic circuit for the lower frequency.

It is well to note at this time that the number of phases of the circuit supplying the motor has nothing to do with the speed at which it operates.

SINGLE-PHASE MOTORS

Single-phase motors may be classified according to the three following groupings: (1) series; (2) induction; and (3) repulsion. Taken as a whole the induction type is much more numerous than the others although certain fields of application may be almost wholly supplied with one type. The small motor-driven tool and appliance industries use enormous quantities of series type motors with some companies making a specialty of this particular motor. The induction type is used in practically all applications where constant speed is desirable, as this motor is like the shunt in this characteristic. The repulsion motor provides better starting than the induction type and is also widely used where variable speed is required from an alternating-current source of power. Many types of repulsion motors have been developed, over half of which are now obsolete. Practically all companies making alternating-current machines make a repulsion motor. Some of these are discussed later in this lesson.

Torque. An induction motor may have running torque but has little or no starting torque. Why this condition exists is explained by Fig. 1. A squirrel cage rotor is used in this illustration as it simplifies the diagram, and the theory is exactly the same whether the armature is wire wound or made up from short-circuited bars. Fig. 1 shows a 2-pole stator with single-phase winding connected to lines L1 and L2. During one-half cycle the current is flowing into the stator winding from L1. This makes the top half of the stator a north pole and the lower half a south pole.

The flux in the stator, set up by the current during the first half cycle, will cut the rotor bars and induce currents in them as shown in *A*, Fig. 1. As these bars are short-circuited by end rings, currents will flow in the bars and cause the rotor to be polarized with a north pole, N, at the top and a south pole, S, at the bottom, as in *B*, Fig. 1. This position of the rotor poles with reference to the stator poles with north pole N at the top and south pole S at the bottom will produce no torque in the rotating member because the rotating forces are equal and in opposite directions.

During the next half cycle the polarity conditions of both stator and rotor will be exactly reversed and no starting torque will be produced.

As long as the rotor and stator poles have this relationship, no torque can be developed, because some angular displacement of the rotor and stator pole positions must take place before any turning action becomes effective. How this displacement of the poles on the stator and rotor is effected for starting will be explained under split-phase motors.

The single phase motor differs from the polyphase motor in

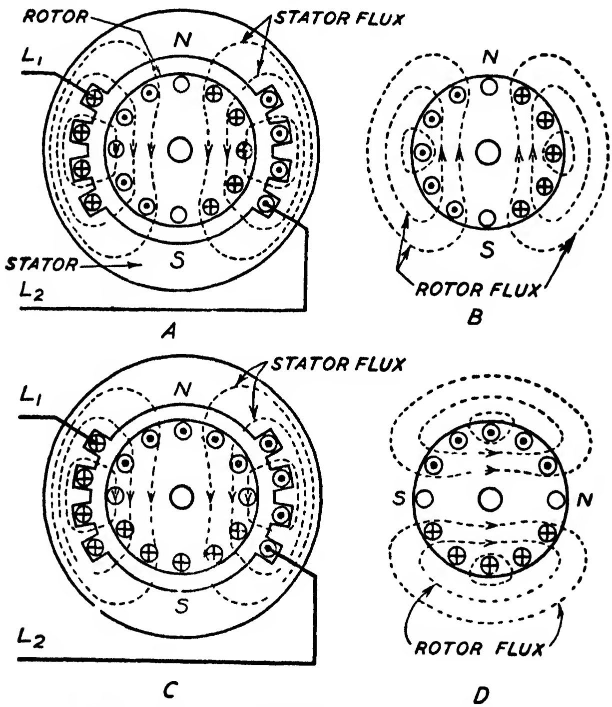


Fig 1 Direction of Flux Paths in Stator and Rotor

the following respect. The poles alternate in the single phase machine while the stator flux rotates when more than one phase is used.

Figure 1, C and D shows the relative positions of stator and rotor polarities when the rotor is driven at synchronous speed in the changing field of the frame. In the case of a two-pole motor, the rotor would have to be turned once for each cycle. This rotation of the moving member causes the polarity to be at right angles to the stator poles. The main poles are located at the top and bottom while the induced poles are on the right and left sides of the rotor.

This is the position which produces the maximum torque. Just why the rotor poles are now at right angles to the main poles is rather difficult to understand. This shift of poles from positions in Fig. 1 to the positions they now occupy is caused by the rotor rotation.

Figure 2 shows the stator flux polarity on the second half of the cycle resulting from the current supply furnished by L_1 and L_2. This figure shows the rotor flux condition at very nearly synchronous speed. The rotative affect has now caused the rotor polarity to shift almost 90 degrees with reference to the stator polarity. A comparison of Fig. 2 with Fig. 1 will clearly indicate this fact.

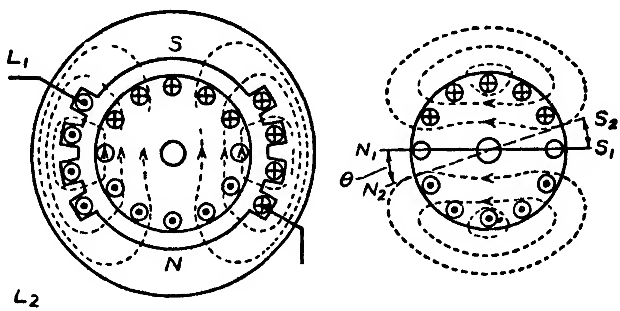


Fig. 2. Direction of Flux when Stator Current Is Flowing from L_2 to L_1 and Rotor Running at Synchronous Speed

This relationship of rotor pole position with stator pole position results in maximum available torque. The angle θ between the true 90 degree position and the actual pole position is caused by the slip. In any motor where the rotor field is produced by the flux of the stator setting up a voltage in the rotor winding, the revolving or changing field must rotate faster than the moving element of the machine. Otherwise, no flux could cut the rotor and no voltage would be produced to force current through the circuits in the armature of the machine. This difference in speed between the revolving field and the rotor is called the slip. This usually varies from two to seven per cent on well-designed squirrel cage machines. It is seldom over four per cent on three-phase motors of this type.

Series or Universal Motor. Figure 3 shows the diagram for a series or universal type of single-phase motor. This machine is almost identical with a direct-current series motor. The alternating-current conditions require that these machines have laminated iron pole pieces as well as the laminated armature. This construction

eliminates eddy currents in frame and pole pieces. In this motor both the stator and the rotor are magnetized from the line current.

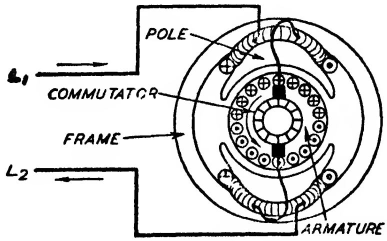


Fig 3 A Series on Universal Motor with Current Flowing as Shown by Arrows

When the current reverses in one part of the machine, it reverses in the other at the same time. This means that the operation with alternating current is essentially the same as though direct current was operating it. Fig. 4 shows the conditions in the series diagram in Fig. 3 on the second half of the cycle only. The direction of the current is reversed, but the polarity relationship between the armature and the stator are relatively the same so the torque is developed regardless of the current direction through the motor.

Thus, it is very essential that the direction of magnetism in the field and armature reverse at the same exact instant, because if one reversed first the direction of the torque would be reversed momentarily.

Universal motors will have somewhat different load speed characteristics on direct current than on alternating current. The inductive effects present in the alternating-current circuit will cut down the current and reduce the speed below what it would be on a

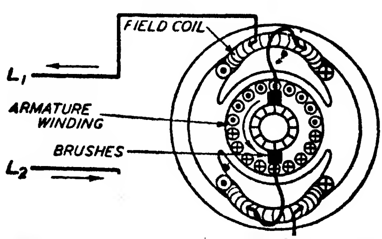


Fig 4 The Direction of Current Flow One-Half Cycle Later Than in Fig 3

direct-current circuit of the same voltage. Motors of this type are used principally on small appliances such as drills, scrubbers, blowers,

vacuum cleaners, sewing machines, mixers, etc. To meet these types of service, capacities from 1/150 to 1 horsepower have been developed. Universal motors have high starting torque and operate most efficiently at speeds of 4000 to 10,000 revolutions per minute, speeds possible only with small armatures. Fig. 5 shows the parts of a universal motor just described.

Many applications where universal motors have been tried show

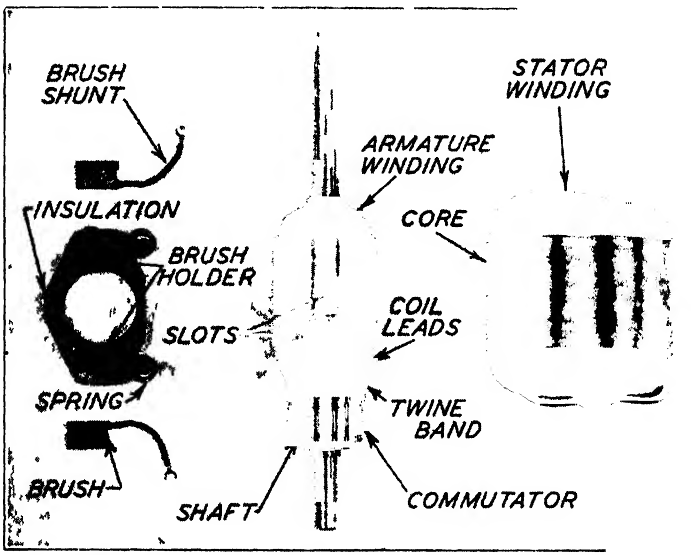


Fig. 5. Parts of a Westinghouse Type AD Universal Motor

unsatisfactory results on account of the wide difference of the speed behavior of the motor when operating on direct and alternating current. To meet this condition, many concerns make two motors, one of alternating-current and the other for direct-current use. These are interchangeable so far as dimensions are concerned. This development indicates that considerable judgment must be used in universal motor application.

Larger capacity universal motors require an additional winding on the stator to cut down the high inductive effects at the brushes. This winding, called a compensating winding, is wound so that its field will neutralize the field of the coils being commutated, thus helping to reduce abnormal sparking. This would make the compensating winding 90 degrees from the main or stator windings. It

is connected in series with the main winding and armature. The high resistance of the small motor coils takes care of the inductive effects on small machines, but the low coil resistance and higher voltage usually used aggravate sparking at the brushes on larger motors of this type requiring a neutralizing winding to enable the machine to operate satisfactorily.

Series motors used on alternating current have considerable advantage over direct-current series motors. Through the use of a transformer with a number of taps on the secondary, the voltage at the motor terminals may be efficiently changed. This variation of the motor terminal voltage provides a wide range of speeds obtainable with the alternating-current motor.

A large universal motor has been successfully developed for railway work The direct-current voltage of 550 volts is used from the trolley on city streets and 1300 volts can be used from a transformer when the car runs in interurban territory. This motor gives very satisfactory operating characteristics on either system and is widely used for this type of work.

Split-Phase Motor. The split-phase motor is a squirrel cage motor with two windings on the stator, one of which is the running winding and the other the starting winding. A glance at Fig. 1 shows the conditions in the stator and rotor magnetic circuits with the like poles on each, exactly opposite, producing no starting torque. One of the most common methods of obtaining a displaced polarity condition between the rotor and the stator fields, to bring about torque for starting purposes, is to add another set of coils to the stator as shown in Fig. 1.

These coils are wound 90 degrees from the original set and are connected to the power circuit only during the period of starting. The leads to this switch are disconnected from the line by a centrifugal switch as soon as the motor reaches about 85 per cent of synchronous speed and remain off the line until the speed drops to approximately 60 per cent of normal when they will be cut in on the line again by the switch. Unless the speed comes up to normal in a short time after the reduced speed, this winding may burn out.

The running winding *R* shown in Fig. 6 is the same winding as shown in Fig. 1. The starting winding *X* is wound between the coils of the running winding *R* and has high resistance and low induc-

tance while R has a low resistance and high inductance. This will give the two windings a phase displacement of the two currents flowing in the running and starting coils approximating the conditions in a two-phase circuit. Instead of the polarity of the stator winding shifting 180 degrees and changing the polarity of the main winding to a like amount, this additional set of coils causes a shifting of the magnetic flux only 90 degrees for a half cycle change in current.

In Fig. 7, consider R the running winding to be phase 1 and the starting winding X to be phase 2. The current in R is at a maximum value positively while the current in X is just ready to start

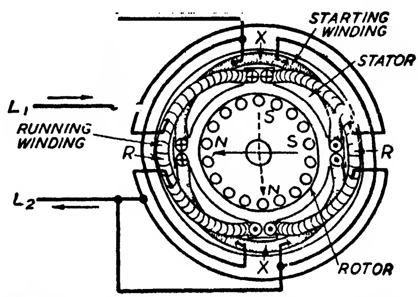


Fig. 6. Diagram of a Single Phase Motor with Starting and Running Windings

positively. As the current in R gets smaller, weakening its magnetic effect, the current in X is getting larger, strengthening its magnetic effect. The result is a polarity which moves around the rotor in a clockwise rotation.

This in effect is a rotating magnetic field around the rotor which cuts the rotor bars setting up local circuits in this element, polarizing it. These magnetic poles set up in the rotor tend to follow the main poles and a starting torque is produced. While this torque is weak compared to the running torque developed, as the rotor approaches synchronous speed, it is sufficient to start light loads found in many types of motor applications where fractional horsepower motors are used.

Split-phase motors are made only in fractional horsepower sizes for use where small amounts of power are needed from a single-phase lighting circuit. The starting torque is too low to start only very light loads, and the starting current is high, which causes line voltage disturbances. In some applications, a clutch disconnects the motor

from the load until it is up to speed where it has normal torque.

Condenser in One Leg. Some split-phase motors are wound with two sets of coils like a two-phase motor as shown in Fig. 7. As the currents in coils *R* and *X* normally would be in phase from a single-phase source, resistance and capacity are introduced in coil *X*. This causes the current in coil *X* to lead the voltage which would result in a phase angle between the currents in the two coils. The resulting magnetic poles moving around the stator would develop starting torque, and the motor would operate very similar to a two-phase machine. This type of starting for split-phase motors is more expensive than starting winding with the switch, but it improves

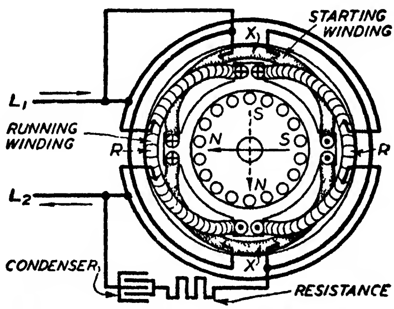


Fig. 7. Method of Connecting a Condenser and Resistance in a Split-Phase Motor

power factor, efficiency, and slip, as this motor acts more like a polyphase induction motor.

In order to increase the effectiveness of the condenser for starting, in some cases an auto transformer is used to raise the voltage across the condenser terminals to three or four times normal. The condenser is sometimes left in the circuit with line voltage across the terminals while the motor is operating, as this improves efficiency and power factor of the motor.

Figure 8 shows a capacitor-start induction-run motor for use in refrigerators, stokers, oil burners, and other household appliances where higher starting torque is required than is obtainable with the split-phase motor. There is also less radio disturbance from this motor than is caused by the split-phase machine.

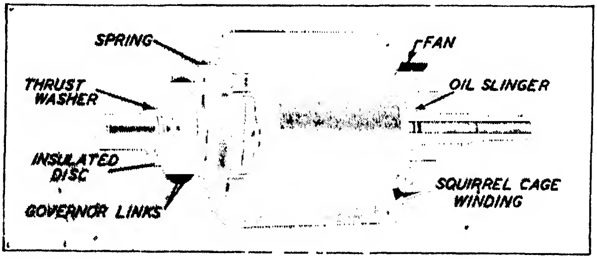
Reactance in One Leg. Reactance may be used in one leg of a two-phase winding for starting on single phase. This consists of a choke coil connected in one phase of the winding on the stator.

This lagging of the current in one phase caused by the choke makes displaced phase relations between the currents in the two coils on the stator windings which sets up the starting torque in the rotor. In some cases a choke is used in one leg as a current limiting device when the condenser is utilized for starting. This tends to limit line disturbance but cuts down the starting torque of the motor.

Fig 8. Wagner Single Phase Induction Motor with Electrolytic Condenser Mounted on Top

Resistance Wire. The use of resistance wire in the winding of the stator has been used in a few small motors to obtain this split-phase condition for starting. A few coils of resistance wire have been interspersed in the main winding to produce starting torque. Motors of this type have usually been fan motors in which efficiency is a minor item in the operation. Better methods have been developed which have made this type of construction nearly obsolete. High resistance leads, from the coils to the commutator segments, are sometimes used with single-phase straight series motors to reduce sparking which is especially bad during the starting period.

Squirrel Cage Rotor. Practically all motors of the split-phase type, now being manufactured, use the squirrel cage rotor and the wound stator, as this method of construction has proved much superior to the reversed scheme of the squirrel cage stator and the wound rotor. Fig. 9 shows clearly the main windings, the starting



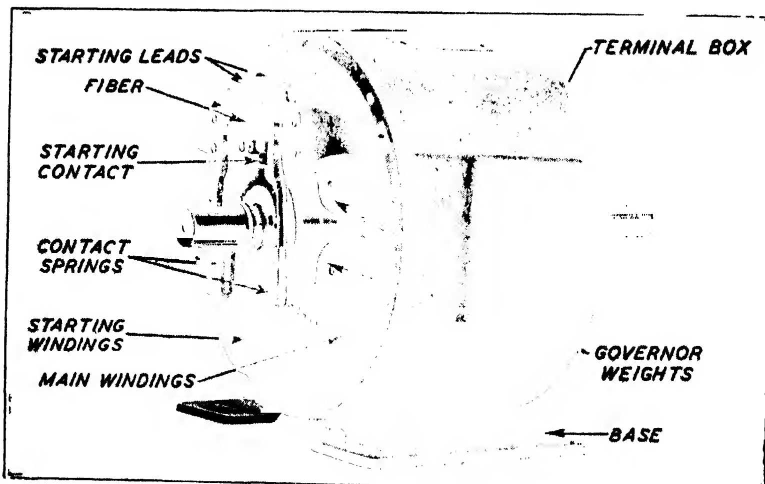


Fig. 9. (Top) Rotor of Century Split Phase Motor Showing Governor Which Opens Starting Windings
(Bottom) Rotor Assembled in Stator Showing Arrangement of Open-Circuiting Device
Courtesy of Century Electric Company

windings and the open circuiting switch operated by the rotor of a motor of the split-phase type.

Split-phase motors with the squirrel cage stator and the running and starting coils on the rotating member were made quite extensively by the General Electric Company up until a very few years ago. Due to the fact that the coils could be machine wound, the cost of construction for this type of motor was very low and therefore large

quantities of these motors were sold. The construction shown, Fig. 10, required the power supplied to this machine to be passed through the carbon brushes to the bronze rings as shown on the rotor. Trouble was experienced from brush and ring wear with the resultant sparking causing considerable radio interference.

There are two classifications of alternating-current commutator motors—those in which the speed materially changes with the load are called series motors, and the others in which there is only a slight change in speed with load are termed shunt motors. The latter type

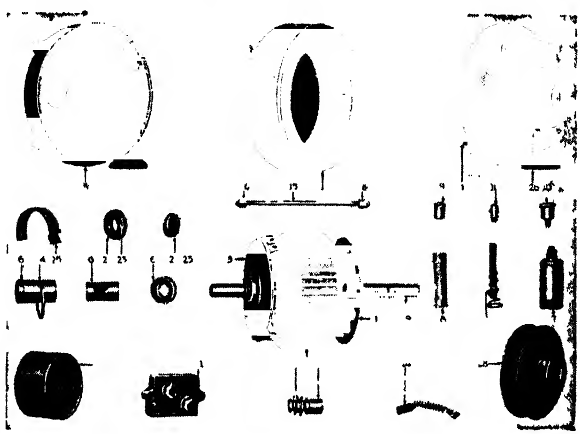


Fig 10 General Electric Type SA Single-Phase Rotor

may be connected with auxiliary equipment which provides a variable voltage through which the speed may be increased or decreased independently of the load. They are still classified as alternating-current shunt motors however. Many of the repulsion type motors discussed later in this lesson fall in the latter classification.

Repulsion Motor. The repulsion motor has the stator coil connected to the line. The armature is wound like a direct-current machine but has no connection to the line. Short-circuiting brushes provide an armature circuit which has an electromotive force across it because of the magnetic effects of the stator winding. The poles set up by the induced current in the rotor are the same polarity as the stator poles. The torque is set up by the opposing forces between these sets of like poles from which comes the name *repulsion motor.* A series motor, with the stator winding connected to the source of supply and the armature short-circuited, would become a motor of

this type. The repulsion motor finds a wide field of application where comparatively high starting torque is essential. A great many modifications have been made of the original repulsion motor developed by Elihu Thompson as early as 1887. Fig. 11 shows a diagrammatical representation of this early motor. The armature is provided with a pair of brushes for each pair of poles on the stator

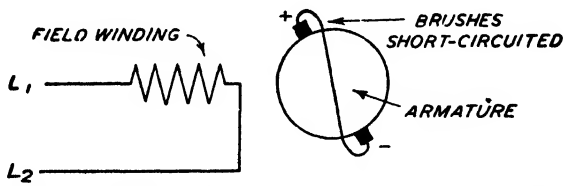


Fig. 11. Diagram of Circuits in the Early Repulsion-Induction Motor

winding. All positive brushes are short-circuited with all negative brushes.

Currents developed in the rotor, through the action of the stator flux, will develop torque in any position of the brushes between poles except at the halfway point. Here as much rotative effort will be developed in one direction as the other; therefore, the result will be zero and no torque will result. This is made clear from an inspec-

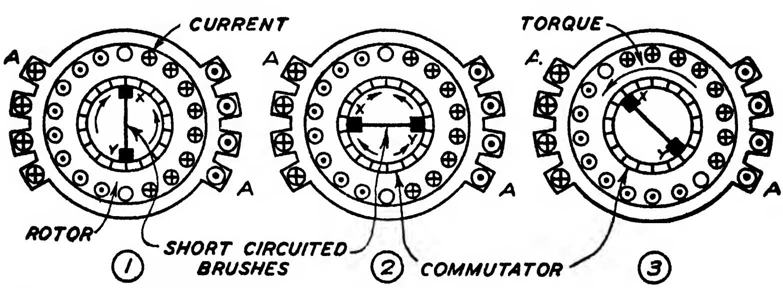


Fig. 12. Diagram Showing the Direction of Induced Voltage, Current, and Torque in a Repulsion Motor

tion of Fig. 12. This shows stator coil *A* setting up a magnetic field across the rotor which changes polarity with the frequency of the supply circuit. This induces an electromotive force in the rotor windings. With brushes as in position (1) the electromotive force developed in the right side of the rotor will be exactly equal and opposite to electromotive force in the left side of the rotor. With

brushes set at the position where these electromotive forces meet, a large current will flow, but no torque will be developed because the turning effort on the two sides of the rotor balance each other. If the brushes are now moved into position (2), we have a condition of balanced voltages across the brushes as shown by the two sets of arrows and no current flows through the short circuit. With brushes

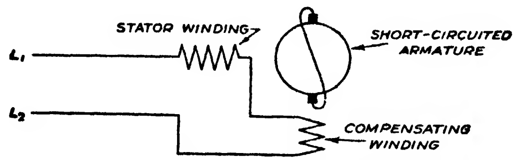


Fig 13 Diagram of Circuits of an Atkinson Repulsion Motor

in position (3), the condition of unbalanced voltage would cause current to flow through the short circuit and the turning effort would be more in one direction than the other, so useful torque would result causing the rotor to turn.

ATKINSON MOTORS

The Thompson or original repulsion motor worked satisfactorily as long as lower voltages and small sizes were made. When larger sizes were made and higher voltages were applied to these motors,

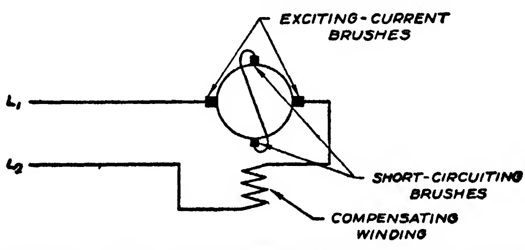


Fig. 14. Diagram of Circuits of Latour-Winter-Eichberg Repulsion Motor

a great deal of commutator trouble developed from the large inductive effects on the short-circuited coils. The compensating winding was found to be a satisfactory solution for this trouble in the alternating-current series motor, so Atkinson applied the idea to the Thompson motor. The result is the conductively compensated repulsion motor shown in Fig. 13. Another variation of the compensated single-phase repulsion motor is shown in Fig. 14. This

motor employs two sets of brushes, one to pass the line current through the armature like a series motor and the other to short-circuit the armature to produce the repulsion effect. This idea is jointly credited to men by the names of Latour, Winter, and Eichberg.

The advantage of the last arrangement is in the elimination of the stator coil; the armature winding is made to furnish this field more effectively than was the case with a stator winding.

All of the repulsion motors discussed have the direct-current series motor characteristic of losing considerable speed as the load is applied.

REPULSION-START INDUCTION-RUN MOTORS

The repulsion-start induction-run motor is by far the most numerous of all the various types of single-phase motors. This machine has the operating characteristics of the induction motor with starting torque from two to five times full load running torque. For the same line current it has higher starting torque than any other type of single-phase motor. Its maximum torque varies from 2 to 2½ times full load torque and its pull in torque from 1½ to 2¼ times its full load value.

The stator is usually wound with two sets of coils which makes possible the use of the motor on either 110 or 220 volts by simply connecting the coils in parallel or series. The stator core is high-grade steel laminations riveted together under pressure. The cores of these machines are usually insulated and completely wound before being inserted into the frame. This type of construction makes repairs simply and quickly made, as a spare core may be kept on hand to replace burn outs.

Frames are usually rolled from steel sheets, as this provides greater rigidity with less weight than is possible with cast frames. The feet are welded to the frame. Various types of vibration absorbing bases are available for special applications where noise is objectionable. Some of these use steel spring mountings and others are set in rubber.

The armature for repulsion-start induction-run motors is made of laminated iron and wound with coils like a direct-current or repulsion type machine. The commutator is provided with a short-

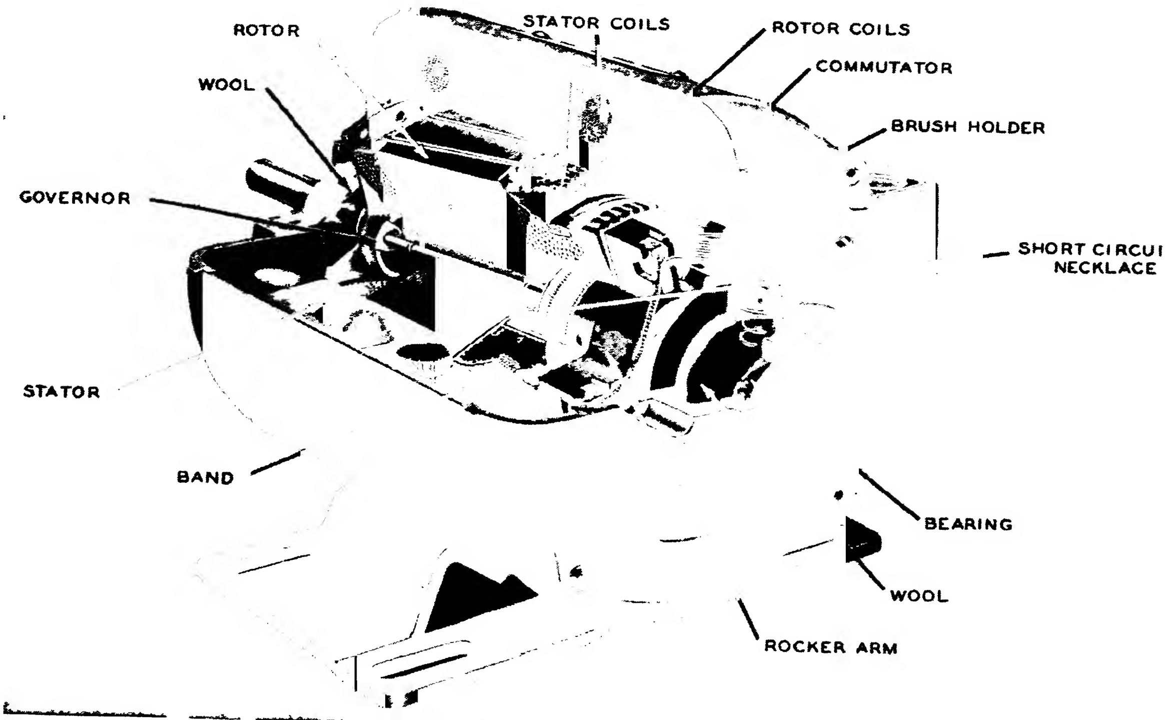


FIG 15. CUTAWAY VIEW OF A WAGNER, REPULSION-START, INDUCTION-RUN MOTOR
Courtesy Wagner Electric Corporation

circuiting device which short-circuits the coils and makes the machine function like a squirrel cage induction motor once it is up to speed. The short-circuiting device is operated by a centrifugal switch which forces a copper ring, made of small segments, against the commutator bars after the proper speed is reached. This is usually about 80 per cent of syr‘hronous speed but varies with different motor manufacturers.

End type and ring type commutators are both used with repulsion-start induction-run motors. Some are made to throw the

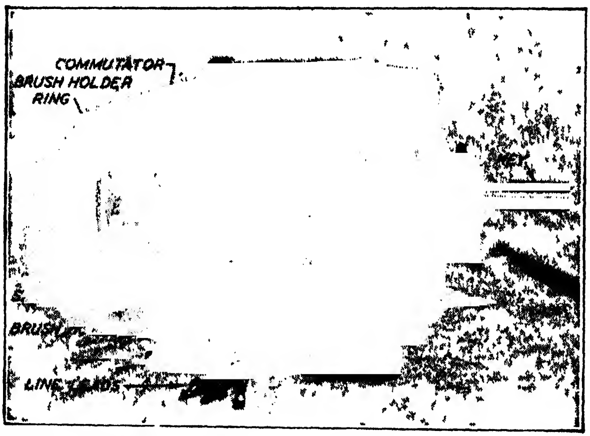


Fig 16 Westinghouse Type CR Induction Repulsion-Start Motor

brushes clear of the commutator, while others ride the commutator continuously. No matter what commutator type or brush riding arrangement is used, all of them short the commutator to make the rotor function as an induction machine while operating. During the starting period, the line current either passes through the armature as in Fig. 13 or excites the armature through induction as in Fig. 12, producing like poles on both rotor and stator. The repulsion effect sets up the high starting torque characteristic of these motors.

Figure 15 shows cutaway section of a repulsion-start induction-run motor built in sizes of ⅛ to 40 horsepower. This machine has the end commutator with brush lifting rigging used in a very large percentage of these motors. Fig. 16 shows a motor with the ring type commutator on which the brushes ride permanently but carry

current only during the starting period. These machines are built in capacities from $\frac{3}{4}$ to 3 horsepower.

Some of these motors are built with an inner squirrel cage winding which improves the torque curves of the straight repulsion-start motor. The outer winding connected to the commutator provides the initial starting torque and assists the inner squirrel cage winding by carrying its share of the rotor current while running. This construction provides a motor with very smooth-speed-torque curve with sufficient torque to bring up to speed any load it can start. The speed is nearly uniform from no load to full load.

Repulsion-start induction-run motors are used for a great variety of purposes, a few of which are given as illustrations: compressors; pumps; farm machinery; ventilating fans; blowers; machine tools; grease guns; car washers; lifts; oil burners; and refrigerators. Wherever there is a difficult power job to be done and only a single-phase source available, this type of motor will nearly always be found taking care of it.

GENERAL ELECTRIC REPULSION-INDUCTION MOTORS

The General Electric Company make single-phase repulsion-induction motors with two types of compensating windings. One type has an independent compensating circuit, while the other takes a tap from the main stator winding to neutralize induction. Both of the motors are a modification of the original Thompson motor. The compensating circuits used in this motor improve not only the power factor but also the speed characteristics of the original motor, both of which were very poor. This motor is not a constant-speed machine but is designed to approximate the speed characteristics of a compound direct-current motor. The starting torque varies from 2 to $2\frac{1}{2}$ times full load torque. It may be connected directly across the line, but a resistance type starting box may be used if direct starting causes too much line disturbance.

The brushes ride the commutator at all times, and the motor may be reversed if the brushes are rotated far enough in any one direction. This motor is built for reversing by using a switch and adding another winding to the stator at 90 degrees to the original one. Whichever direction the current flows through this winding, with reference to the original stator winding, will determine the direction

of rotation of the motor. There are two ways of obtaining adjustable speed for these repulsion-induction motors. The brushes may be shifted, or through the use of a transformer with taps which changes the terminal voltage. For some applications, both the transformer with taps and a brush shifting device are employed to obtain adjustable varying speeds. Fig 17 shows a motor of this type for operation on either 110 or 220 volts with a speed variation of 2½ to 1. It is

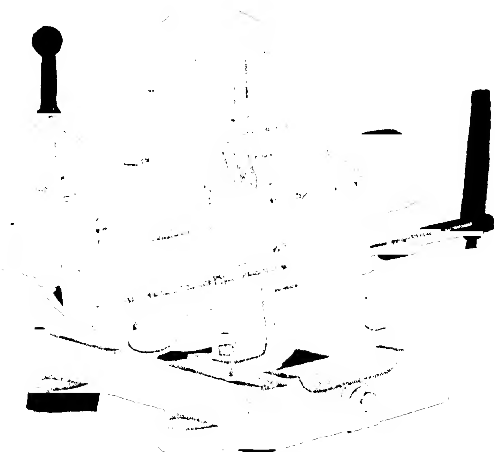


Fig. 17. Single Phase Motor in Which Speed Adjustment Is Obtained by Shifting Position of Brushes
Courtesy of General Electric Company

either reversible or not reversible as required in sizes varying from ¼ to 2 horsepower.

The starting torque will vary with the brush position and will be from 1½ to 3 times full load torque for 4-pole motors and from 1¼ to 2½ on 6-pole motors. The maximum torque obtainable from this type of motor will be approximately 3½ times full load torque. Because this is a constant torque motor, the horsepower output will be proportional to the speed. The no load speed of this motor is about 1.6 times synchronous speed. Unless the motor is properly loaded the speed variation will not be obtained as the series characteristics will over speed it. Its principal fields of application are in the operation of printing press machinery and testing equipment.

A larger motor for use on polyphase distribution systems is shown in Fig. 18. It can be obtained regularly in 3 to 1 speed ranges but is also available in other speed ratios. These motors have shunt

field characteristics which open a wide field of application requiring speed variations. Examples of lines powered by these motors are: baking machinery; boiler-house fans; cement kilns; conveyors.

Fig. 18 General Electric Type BTA 3-Phase Adjustable Speed Motor with a Small Pilot Motor for Shifting the Brushes

CENTURY REPULSION-INDUCTION MOTORS

The Century is not a repulsion-induction motor in the same sense that the General Electric motor is a repulsion-induction type. The Century machine is, strictly speaking, a repulsion-start induction-run motor. It operates on the principle of a repulsion motor when starting. Fig. 19 at (*A*) shows the position of the short-circuiting necklace and brush mechanism at the starting. The 4 brushes (2 pairs) bear against the commutator and provide an armature circuit for the voltage and current induced in the armature windings. When armature approaches full speed, centrifugal governor weights are thrown outward and operate a push rod that moves the short-circuiting necklace. This necklace joins all commutator bars together, thus short-circuiting the bars and changing the armature winding into a squirrel cage rotor. The motor at full speed operates on the induction principle, as does the squirrel cage motor. The 4 short-circuiting brushes are no longer needed to provide a circuit and may either remain in contact with the commutator or be pushed away from it; however, the life of the brushes is increased many years if they are pushed clear. The running position of the brushes and short-circuiting necklace is shown in Fig. 19 at (*B*); at (*C*), is a detail of brush mechanism, short-circuiting necklace, and barrel.

Starting torque of the repulsion-start induction-run motor is from 2½ to 3½ times full-load torque. Starting current will not exceed 3½ times full-load current when motor is connected directly to line. The only sparking at the brushes is for a few seconds when motor is starting, limiting radio interference to that short period. Torque characteristics of repulsion-start induction-run motors make

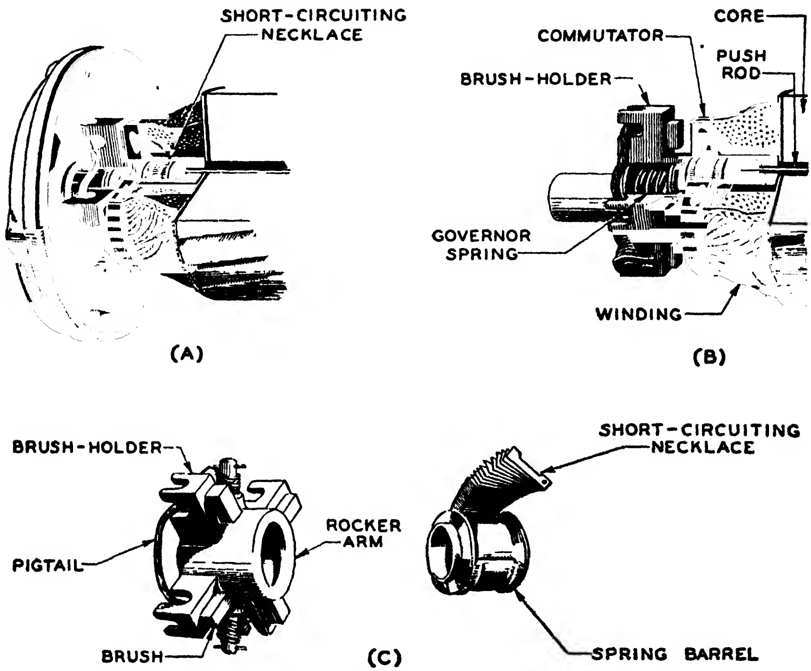


Fig. 19. Parts of a Repulsion-Start Induction-Run Brush-Lifting Motor

them adaptable to operation of plunger pumps, compressors, oil burners, and refrigerating machines.

WAGNER REPULSION-INDUCTION MOTORS

The Wagner Electric Company makes a line of motors very closely paralleling the Century line. Their repulsion-start induction-run motors are made in sizes from $1/10$ to 15 horsepower in all standard voltages and frequencies. The frame is of rolled steel and welded construction into which the wound stator core is inserted. The stator iron is high-grade annealed sheet made especially for the

work. Fig. 20 shows a section of the Wagner repulsion-start induction-run motor stator. Note the excellent coil fit in the slots and the maple wedges holding the coils firmly in place. These

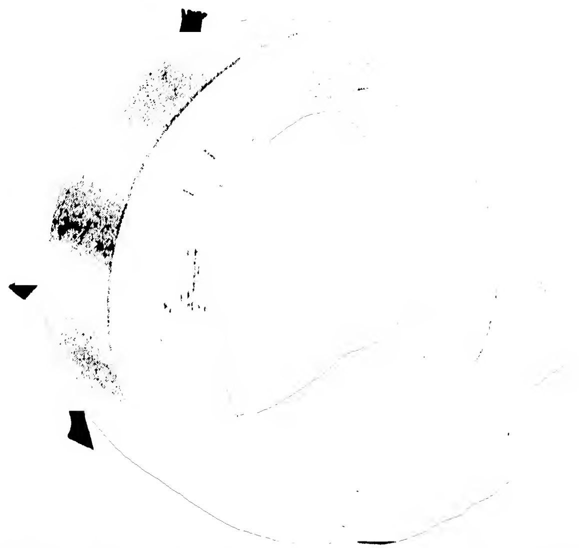


Fig. 20. Arrangement of Winding the Pole Groups in the Stator
Courtesy of Wagner Electric Corporation

stators are thoroughly impregnated with insulating compound and baked twice, after which they are thoroughly sprayed with air-dry varnish to increase resistance to oil and moisture.

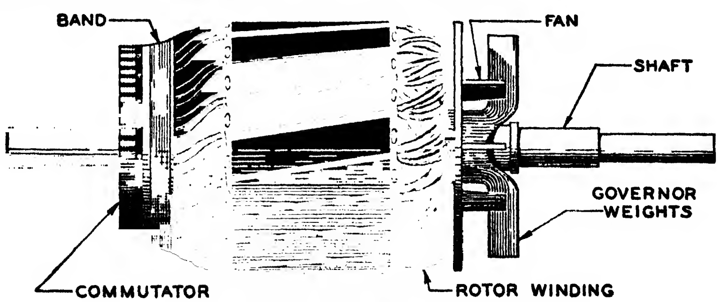


Fig. 21. Rotor of Repulsion-Start Induction-Run Motor

The rotor shown in Fig. 21 is treated and insulated in the same way as the stator. The slots are slightly skewed to reduce magnetic noise and to eliminate variation in starting torque at different rotor positions. The commutator is of the end type construction and is

short-circuited by a necklace of small copper segments forced against the commutator by a centrifugal switch. At the same instant this switch short-circuits the commutator, it lifts the brushes so that no contact is made while the motor is operating at normal speed.

Wagner also makes a straight repulsion-induction motor in capacities of 1 to 3 horsepower. The rotor, in addition to the wire winding like other armatures for repulsion motors, has a regular

Fig. 22. Wagner Type RG Single-Phase Induction Motor

squirrel cage winding. Some of the advantages claimed for this construction of winding are: a smooth speed torque curve, without fluctuations, which makes the motor adaptable for severe starting duty; low starting current; close speed regulation; positive operation on low voltage; excellent efficiency; high power factor; excellent commutation with resulting long brush and commutator life; and no internal short-circuiting mechanism. The brushes must be in contact with the commutator at all times. Fig. 22 shows an assembled view of this late development in repulsion-induction motors

DELCO REPULSION-INDUCTION MOTORS

The Delco repulsion-induction motor is fundamentally the same as the Wagner and Century motors of this type These motors have

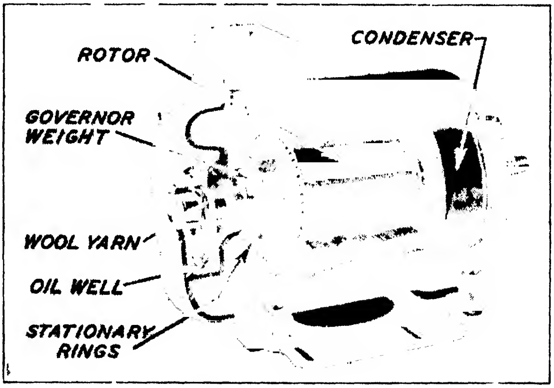


Fig 23 A Capacitor Motor with Internal Condenser The Starting Winding Is Connected to the Stationary Rings and as the Rotor Approaches Full Speed the Governor Weight Moves Outward and Opens the Circuit

Courtesy of Howell Electric Motors Company

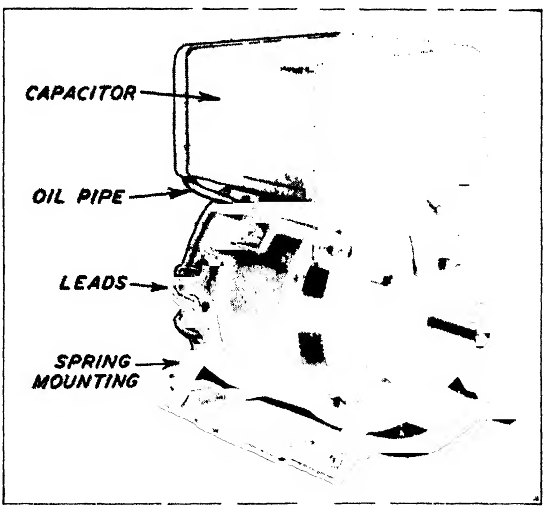


Fig 24 Westinghouse Type FT Single Phase Capacitor Motor The Capacitor Unit Can Be Removed from the Motor and Mounted at any Convenient Location

the end type commutator on the rotor The short-circuiting device throws against the outside of the commutator while running, which is somewhat different than other motors of this kind These machines

are made in capacities from 1/6 to 1½ horsepower and used principally for refrigeration purposes. The following frequencies are available: 25, 30, 40, 42, 50 and 60 with voltages ranging as follows: 80-160, 100-200, 104-208, 105-210, 110-220, 120-240, 125-250, 150-300, 190-380, 220-440.

Capacitor Motor. The capacitor motor was first developed to provide a quiet operating fractional horsepower machine for driving oil burners, pumps, compressors, stokers, refrigerators, and similar equipment requiring high starting torque, long annual run, and high power factor and efficiency. Motors of this type are made with condensers mounted internally and externally. The external mounting is favored especially with smaller units. Capacitor motors are now available up to 10 horsepower, but the condenser unit increases the first cost very materially over repulsion-induction or squirrel cage machines. Figs. 23 and 24 show how condensers are mounted internally and externally with reference to the motor frame.

CLASSIFICATION OF FRACTIONAL HORSEPOWER MOTORS

The National Electric Manufacturers Association has set up the following classification of small motors according to what is called the annual service characteristics of the motors. The two classifications are *long annual service* and *short annual service.* The short annual period is less than 1000 hours per year, and the long annual period is considerably over 1000 hours per year. Motors with long annual service characteristics are intended for use in general purpose applications where the motor is expected to operate at frequent intervals and for long periods of time; where high efficiency and high power factor are desirable; where quiet operation is required; and where normal torque characteristics are needed. Oil burners and refrigerators for household use are very excellent cases. Motors with short annual characteristics are intended for those applications where the motor is expected to operate only at infrequent intervals and for short periods of time. Washing machines and ironers are typical examples of this type of service.

POLYPHASE MOTORS

How the torque is developed for a two-phase motor has already been shown in the explanation of the operation of a single-phase

motor. The only difference between a two-phase winding and a split-phase winding is that the two-phase winding is energized from separate phases of a two-phase circuit while the split-phase is arranged through inductance or capacity to accomplish the necessary current displacement in the two windings. The currents must be out of phase with each other in the two circuits in order to set up torque through the revolving stator field. The two-phase alternator windings are arranged to do this while the single-phase circuit must resort to artificial means to meet the requirements necessary to set up a revolving stator field. The two-phase circuit is far superior to the single-phase for providing starting torque for motors. The three-phase revolving field provided from the three-phase circuit has many advantages over the two-phase system. Installation costs are less; motors have better starting characteristics; power factor and speed regulation is better; and efficiency is higher with the three-phase system.

Where the single-phase motor has one revolving magnetic field set up by the stator, the two-phase circuit provides two fields 90 degrees apart, and the three-phase has three fields each 120 degrees apart. This phase relationship is maintained in the motor stator as well as in the generator windings which makes possible the effective use of the magnetic poles provided by these currents. In a non-inductive circuit, the current curves would have exactly the same phase relationship as the voltage curves, but of course with different values. The introduction of a motor in the three-phase circuit would have practically the same phase displacement effect on the current and voltage in each phase, hence the 120 degree-phase relationship of the currents in each phase would be maintained even though the power factor was poor. How the three-phase winding, with its rotating magnetic field, polarizes the stator through the induced currents is shown in Fig. 25.

The stator winding is placed around the stator with the various phases 60 degrees apart. Reversing the connections to one group of coils sets up the 120 degree-phase relationship which always exists in the three-phase circuit. The current curves for the separate phases are shown in the lower part of Fig. 25. Coils of the stator windings are indicated as *A*, *B*, and *C*. At the first position selected on the sine waves, note that the current in phase *A* is at a maximum

value positively, and the currents in phases *B* and *C* are both negative, but the current in phase *B* is approaching zero while the current in phase *C* is increasing in the negative direction. The induction from these phases causes poles on the rotor indicated by the arrows. Note that the arrows in rotor No. 1 are opposite phase *A* for the first

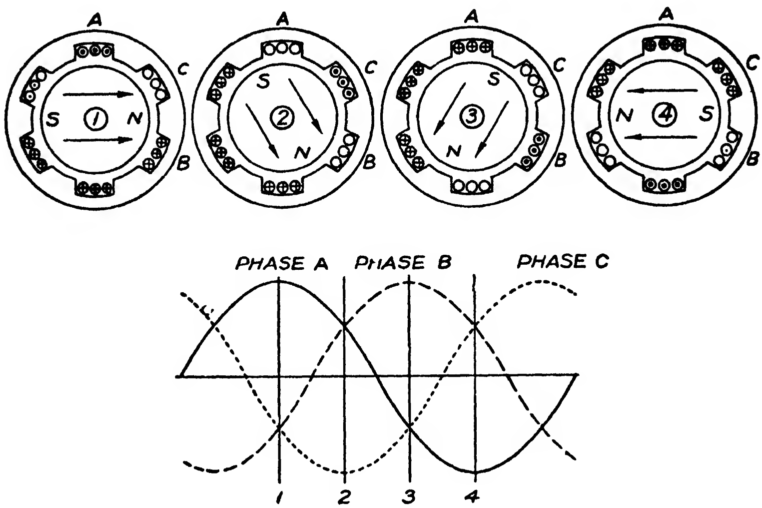


Fig. 25 Rotor Positions During Different Parts of One Cycle

position on the sine curves. Note how these arrows rotate for each of the four instantaneous valves of current as shown by the four rotor positions.

The instantaneous valves of current are taken just 60 degrees apart, which makes the 1st and 4th positions 180 degrees apart. This is a 2-pole winding and the rotor has made just one-half turn from position 1 to position 4. If this stator had been wound with four poles instead of two, the same change on the sine wave would have rotated the rotor only one-fourth of a turn, and a 6-pole one-sixth of a revolution, etc. For this reason rotors used in the stator fields with a large number of poles have slow speeds.

Squirrel Cage Motor. The squirrel cage motor is the most common type of alternating-current motor. It is used in single-phase induction motors, two-phase, and three-phase machines. Properly constructed, it is the least troublesome of any moving element made for motors. The simplest and most common type of

squirrel cage is made by assembling a series of copper rods in the slots of the iron rotor case and welding the ends to a copper ring. If viewed with only the copper assembly, it looks like the old-fashioned squirrel cage from which it got its name. The single-phase motor has been already discussed in this lesson, and the two-phase is becoming scarce; therefore, only the three-phase motor will be illustrated and referred to in the remainder of this work. Fig. 26 shows two standard types of rotors. *A* shows an assembled welded copper bar and *B* shows the cast aluminum type.

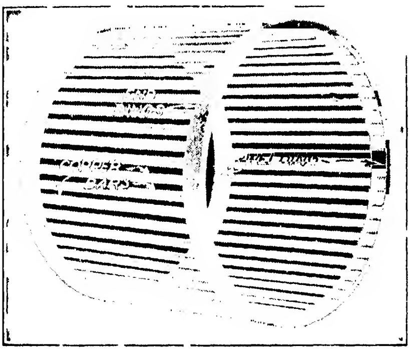


Fig 26*A* Squirrel Cage Rotor as It Would Appear When Removed from the Slots of the Laminated Sheet Steel Rotor Core and Reassembled

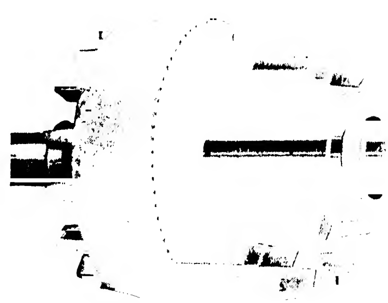


Fig 26*B* Section of Finished Cast-Aluminum Rotor The Molten Aluminum Is Cast in Slots in the Laminated Sheet Steel Core

Courtesy of General Electric Company

The squirrel cage polyphase induction motor is built in any size needed from 1/8 to 5000 horsepower. Voltages are standardized at 110-220-440-550 and 2200 volts and built for frequencies of 25-, 40-, and 60-cycles. Sleeve bearings, ball bearings, and roller bearings may be obtained if desired, although the roller bearings are not standard with all makes of motors. All types of frames, open, semi-enclosed, enclosed, drip-proof, splash-proof, and explosion-proof, are available wherever the application requires. All manufacturers make motors with 40° C. rating and some add a line of 50° C. motors. A 40° C. motor has a 20 per cent greater overload capacity than a 50° C. motor. A great deal of care is taken in the design of all motors to provide proper ventilation for cooling not only the windings but the iron as well. A current of air directed over and through the machine is usually the method employed to dissipate heat losses. Sometimes additional circulating apparatus is used, but ordinarily

fans on the motor are used for this purpose. Fig. 27 shows a partial cross-sectional view of a motor with arrows indicating the direction of air used for ventilation

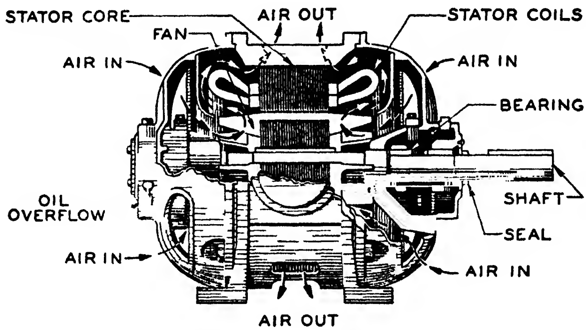


Fig 27 Partial Cross Section of a Fan Cooled Squirrel Cage Motor

Up until a few years ago, a squirrel cage motor was the only motor in the constant speed alternating-current field. At the present time all of the alternating-current motor manufacturers are making at least three and some are making as many as seven types of squirrel cage induction motors

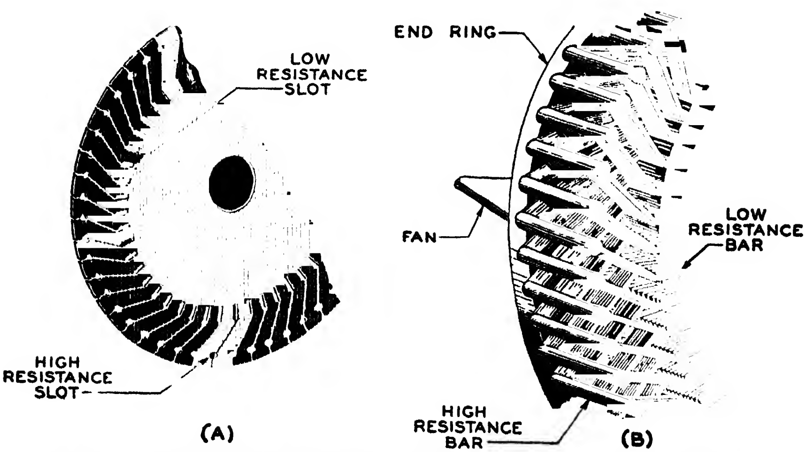


Fig 28 Double Squirrel Cage Rotor Winding At (A) Is a View of Rotor Discs, and (B) Shows Rotor-Windings with Core Removed

The three more common types of squirrel cage motors are grouped as follows: First, the normal torque normal-starting-current

motor. This motor has the highest efficiencies and power factors of all standard lines of induction motors and is more widely used than any of the others. Some type of starting device is usually required to reduce line disturbance when starting. The second group includes the normal torque, a low-starting-current motor designed to do the work of the ordinary motor but start with less starting current. Smaller and more compact control may be employed with this motor. The third group of motors of this type is high-torque, low-starting-current. These motors have a higher percentage of starting torque than either of the other groups, with a starting current no greater than the second group uses. This motor has high full speed efficiency and power factor and is recommended for driving compressors, conveyors, and other loads requiring high starting torque. Fig. 28 shows one rotor construction which will provide the third group of motors with desired operating characteristics. Note the double squirrel cage and large deep slots provided for the low resistance part of cage.

In Fig. 29 the comparative table gives a picture of the conditions developed in various types of squirrel cage rotors by changing the shape of the slots and the winding used. The starting torque, starting current, slip, power factor, and efficiency are the essential factors in analyzing the behavior of a motor. Knowing the motor characteristics is only part of a job of selecting the proper machine to apply to the work. All the operating conditions such as starting, running, power company requirements, voltage, hazards such as explosive dust, flying particles, water and explosive gases must be given consideration before definite decision is made in picking a motor for a job.

The interior view of a squirrel cage induction motor, Fig. 30, gives a very clear picture of the construction, assembly, ventilation, and lubrication features of this type of machine. The frame is welded steel, and stator and rotor cores are made from special laminated steel. The coils are well protected, and the shaft is provided with a circulating fan which directs a current of air over the windings and the rotor and stator steel. All parts are interchangeable for a given size and can be easily and quickly changed whenever necessary. There is nothing to get out of order except possibly bearings and insulation which with proper care rarely happens.

Wound Rotor Induction Motor. The squirrel cage induction

motor provides very little change in speed, only a very limited variation may be made by raising or lowering the terminal voltage. In

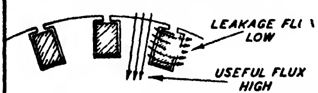
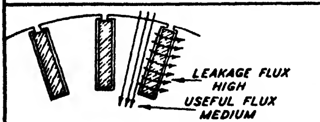
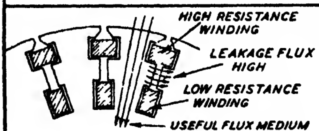
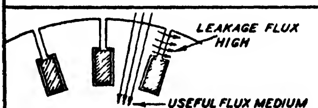
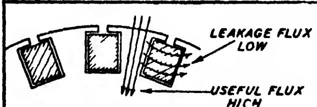
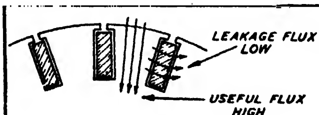
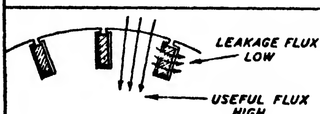
ROTOR AND SLOT CONSTRUCTION	STARTING TORQUE	STARTING CURRENT	SLIP	POWER FACTOR	EFFICIENCY
	NORMAL	NORMAL	LOW	HIGH	VERY HIGH
	NORMAL	LOW	LOW	FAIRLY HIGH	LOW
	HIGH	LOW	MODERATE	LOW	GOOD
	LOW	LOW	VERY LOW	HIGH	HIGH
	LOW	NORMAL	LOW	HIGH	HIGH
	HIGH	FAIRLY HIGH	FAIRLY HIGH	FAIRLY HIGH	FAIRLY HIGH
	VERY HIGH	VERY HIGH	VERY HIGH	FAIRLY HIGH	FAIR

Fig. 29. Different Kinds of Slot and Rotor Construction and the Results Obtained from Them

order to provide a motor for polyphase circuits with practically unlimited speed variation from no load to full load, the wound rotor slip-ring motor was developed. The torque developed by this motor is practically proportional to stator current. This makes the line cur-

rent the lowest for starting of any induction motor. The efficiency is also good at slow speeds, but power factor is low for this machine. The stator construction is standard, as in other types of polyphase motors, but the rotor has a low resistance winding which is connected in phases to three slip rings The control is obtained through the use of a contactor and resistance bank connected to the rings.

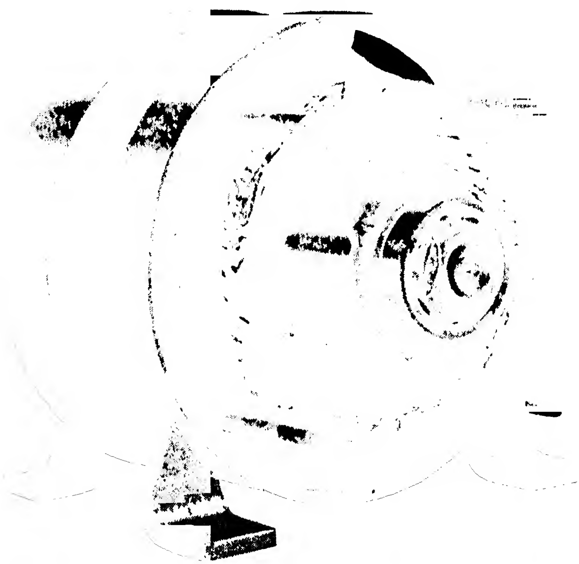


Fig 30. A Squirrel Cage Three Phase Motor with Bearing Bracket Removed
Courtesy of Lincoln Electric Company

Slow speeds are developed when high resistance is introduced into the rotor circuit which increases as the resistance is decreased.

Slip-ring motors are available in all sizes from ¼ to 5000 horsepower for all standard voltages. Through the control they are made reversible speed. They are used on cranes, hoists, and metal rolling mills where reversing duty is essential and where frequent stops and starts are encountered. Because this motor may be "plugged," that is reversed from one direction to the other with power directly from the line, these motors require extra heavy shaft and rotor construction to withstand this abuse. Fig. 31 shows a large heavy-duty wound rotor motor for steel mill service. Fig. 32 shows a partly wound rotor.

Multispeed Motor. The other method of obtaining an alternating-current adjustable speed motor is to use a squirrel cage

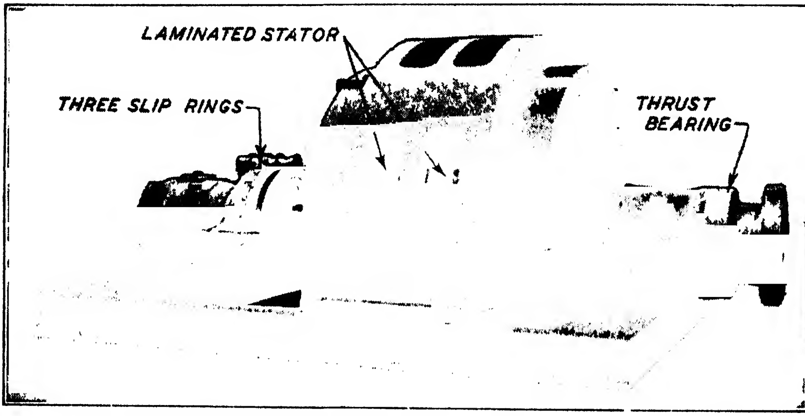


Fig 31 A Westinghouse Type CW Heavy Duty Wound Rotor Induction Motor

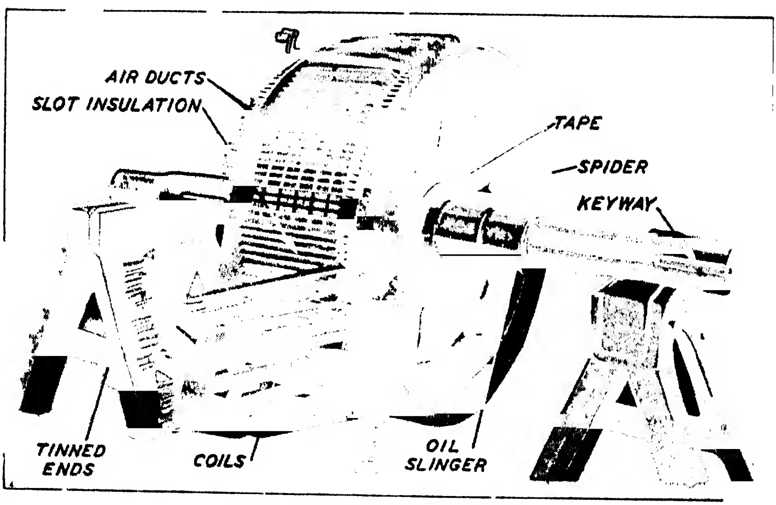


Fig 32 A Partially Wound Rotor
Courtesy of Westinghouse Electric Company

rotor and wind the stator a large number of stator poles. The leads from these coils are brought out to a pole changing switch. In this way as many as two, three, or four definite speeds may be obtained. For example, a 60-cycle three-phase motor may be made to run at

1800, 1200, 900, and 600 r.p.m. Fig. 33 shows a multispeed motor installation with controlled apparatus.

Synchronous Motor. Synchronous motors, like alternating-current generators, are usually built with stationary winding and revolving field which must be excited from some source of direct current. Any alternator can be made to operate as a synchronous

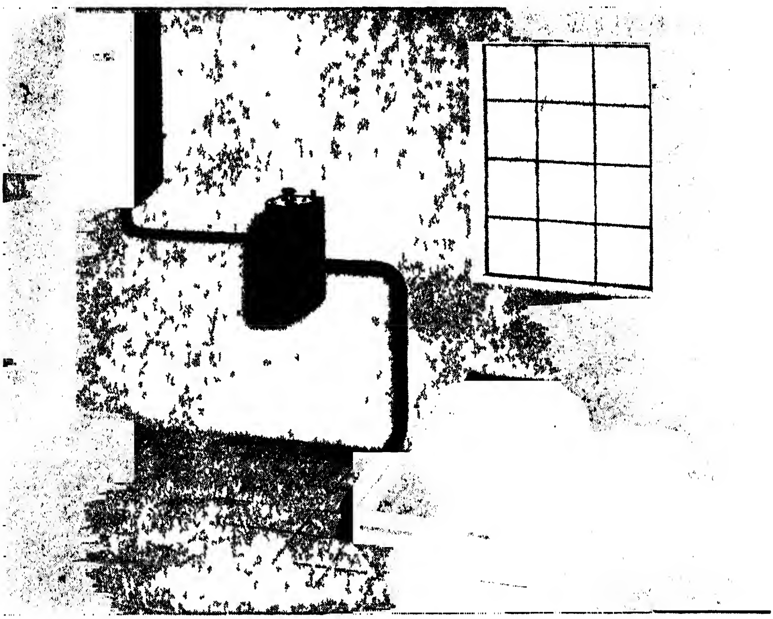


Fig 33. A Multispeed Induction Motor Controlled by a Drum Type Pole Changing Switch
Courtesy of General Electric Company

motor, but trouble due to hunting effects may develop objectionable power surges on the transmission system All synchronous motors develop this tendency to oscillate depending upon the tortional conditions of the load being driven To overcome this trouble, a damper winding is placed in slots in the pole faces This short-circuited winding very effectively eliminates hunting troubles.

The synchronous motor has proved itself more efficient, operates at higher power factor, has absolutely constant speed regulation, and competes very favorably in first cost with other induction motors It is ideally suited for a constant load where speed must be maintained uniform under all conditions By field control the synchro-

nous motor can be made to improve the power factor of a plant or power line and thereby reduce the cost of power, especially where the contract with the power company carries a penalty clause for low power factor.

These motors are built in capacities ranging from 20 to 9000

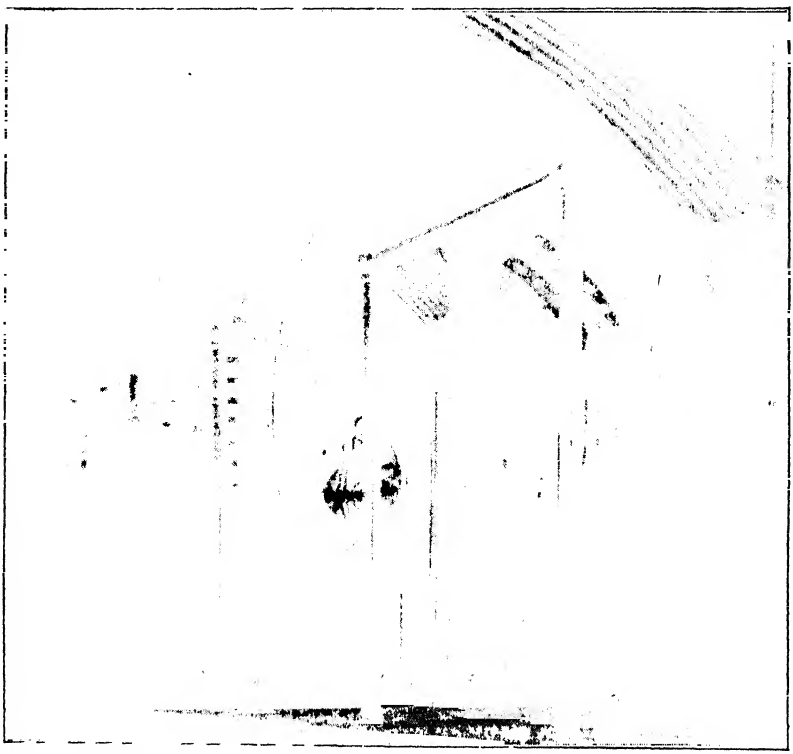


FIG. 34. A 600 Horsepower, Synchronous Motor Having 52 Poles and Operating at a Speed of 138 r p m

Courtesy of Electric Machinery Manufacturing Company

horsepower at speeds varying from 1800 to 60 r.p.m. All standard voltage and frequencies are met in these motors. Synchronous motors are used to drive compressors, paper mills, pumps, blowers, rubber mills, cement mills, mines, steel mills, flour mills, motor generator sets, and oil refining machinery. Fig. 34 shows a large synchronous motor operating a flour mill. The stator frames for practically all these large machines are fabricated from steel plate and welded in the same manner as alternators are constructed.

In the past, the chief objection to the synchronous motor was its lack of starting torque. This has been overcome in various ways. The General Electric Company makes what is called the super synchronous motor, Fig. 35, so arranged that the stator is free to rotate as well as the rotor. In starting, the stator is brought up to synchronous speed and a brake is then applied which gradually slows up the revolving stator as the field is increased in speed.

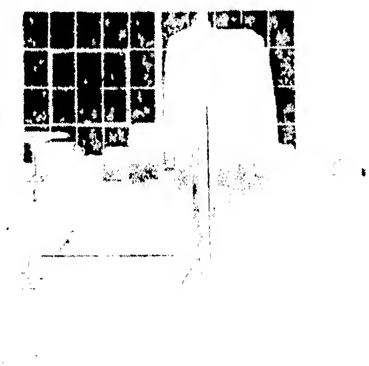


Fig 35 A General Electric 400 Horsepower Type TSR Synchronous Motor. Stator Is Supported on Inner Set of Bearings and Rotor on Outer Set of Bearings

Other companies, by special rotor design with heavy squirrel cage windings in the poles, are now able to successfully build synchronous motors with satisfactory starting torque.

Fynn-Weichsel Motor. The Fynn-Weichsel motor, Fig. 36, developed by the Wagner Electric Co., is a combination of the slip-ring and direct-current motor. The stator has two windings displaced by 90 degrees. One of these windings is connected through an adjustable resistance to the direct-current brushes and the other stator coil is short-circuited with another adjustable resistance. The rotor of this motor, Fig. 37, has two independent sets of windings consisting of a direct-current set of coils connected to a direct-current commutator and a three-phase winding connected to slip rings. Three-phase power is supplied to the slip rings which is the only connection this motor has to the power lines.

In starting, this machine has the characteristics of a slip-ring induction motor. As soon as the machine reaches full speed, the direct current automatically supplied to the stator field from the commutator makes it a synchronous motor. The brushes in field

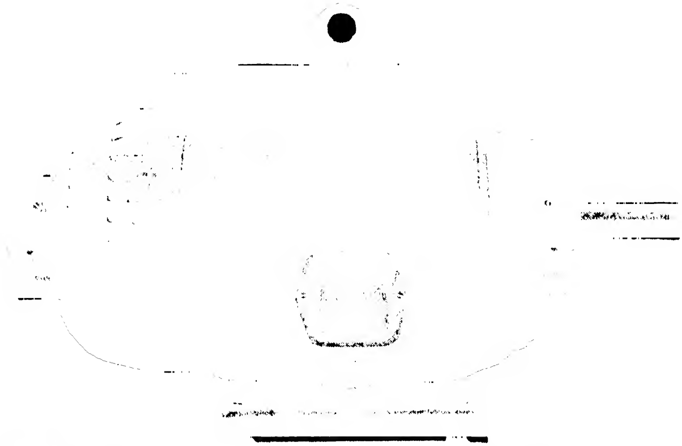


Fig. 36 Exterior View of Fynn-Weichsel Motor with Hinged Cover over Commutator
Courtesy of Wagner Electric Corporation

circuits are set so as to give the motor proper starting torque to meet the needs of the load. This motor has the advantage over the ordinary synchronous motor, being able to operate as an induction

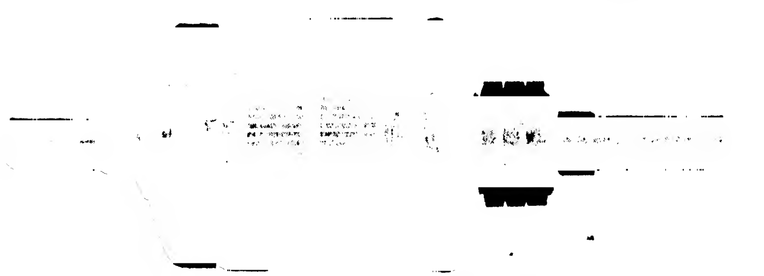


Fig. 37. Rotor of Fynn-Weichsel Motor
Courtesy of Wagner Electric Corporation

motor on heavy overloads, and immediately pull into synchronism as soon as the load becomes normal again. The Fynn-Weichsel motor can be adjusted to have power factor corrective effects on the line by changing the resistance in the direct-current circuit to the stator.

TYPES OF ALTERNATING-CURRENT GENERATORS

The only difference between a simple direct-current generator and a simple alternating-current generator is that the direct-current generator has a commutator and the alternating-current generator has slip rings. From this slight difference in construction comes the difference in the voltage and kind of current obtained from the two units.

FREQUENCY OF ALTERNATING CURRENT

Frequency of an alternating current is the number of cycles the current passes through in one second. A complete turn of a loop of wire will make one complete voltage cycle as shown in Fig. 1. One-

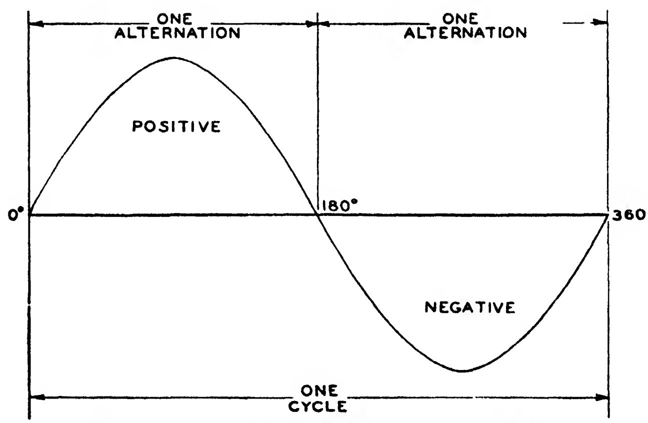


Fig. 1. Curve of Voltage Obtained from Revolving a Loop of Wire between a Pair of Poles

half the rotation of the loop will produce a voltage in a positive direction which causes current to flow out on the outside slip ring, and the next half turn completing the revolution will cause the outside ring to be negative. This shows that the current flows equally in both directions during a cycle. A reversal of current is called an alternation. Two alternations make one complete cycle.

Speed and Number of Poles. If this coil had rotated by two pairs of poles, the effect would have been just the same, as a coil making two complete turns with one pair of poles. Each time a coil or group of coils together pass a pair of poles a cycle is made. Obviously the speed and the number of poles will affect the frequency. Mathematically, frequency equals the poles times the revolutions per second divided by two and is often expressed as follows:

$$\text{Frequency} = \frac{\text{r.p.m.} \times \text{p}}{60 \times 2}$$

If the pole pieces were rotated and the coils remained stationary, the frequency would be exactly the same as it is with the revolving

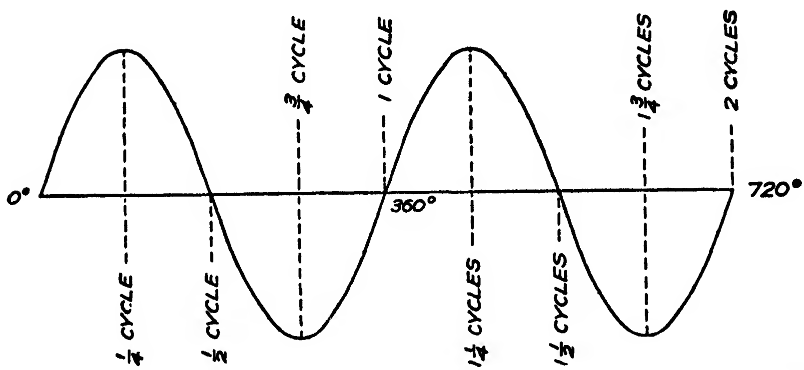


Fig. 2. Curve Showing Variation of Voltage When Loop Makes Two Complete Turns or Two Pairs of Poles Are Used

loop. A pair of poles passing a coil produce two alternations or one cycle, and the coil passes through 360 electrical degrees. If this had been a 4-pole machine, two complete cycles, Fig. 2, would have occurred on the coil or 720 electrical degrees. Each pair of poles adds a cycle to the loop for each revolution that either the coil or the poles make.

Some small alternating-current generators use the revolving armature like a direct-current generator, but for two very important reasons the larger machines without exception use the revolving field in which the poles rotate. One important reason revolving fields are used is due to the fact that insulation stands up better if it is stationary, and the other is no sliding contacts for the large

currents are necessary with revolving fields. Moving parts are also lighter with the latter arrangement. Fig. 3 shows the various positions of the revolving loop with corresponding voltage produced in Fig. 2 for each quarter cycle. No voltage is produced at the first and third positions of the coil as the conductors are not cutting the flux in these positions as shown by Fig. 2. As the coil leaves the starting position, as shown in Fig. 3, the voltage gradually increases

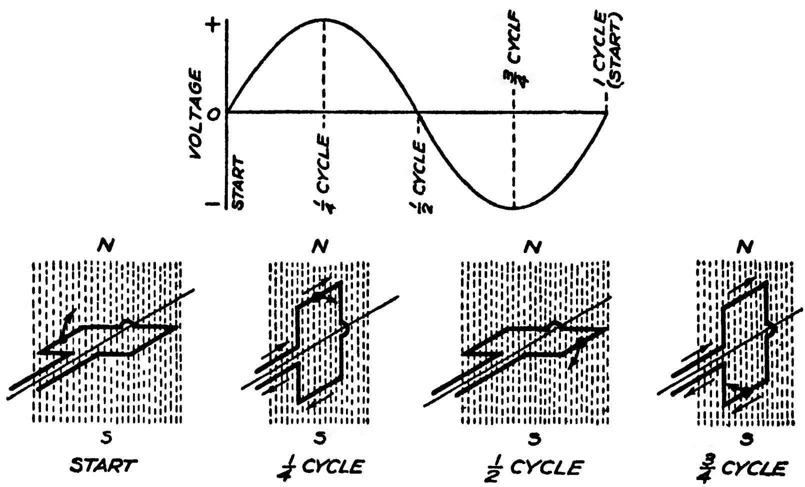


Fig. 3. Loop Positions and Instantaneous Voltages Shown as a Single Loop of Wire Is Revolved in a Magnetic Field

and the second picture shows the voltage at the highest point when the quarter cycle position is reached.

SINE CURVE

The sine curve shown in Fig. 1 is the standard of reference for all discussion on alternating current. This curve can be plotted graphically by using a sine table and the corresponding angles. The sine itself is simply the ratio of two sides of a right-angled triangle, being the altitude divided by the hypotenuse. The cosine referred to in power factor discussions is the ratio of the base to the hypotenuse. Each angle always has the same sine value, likewise a cosine value which is always the same number for any particular angle. A curve plotted from the sine values would always have a maximum value of one.

The sine curve, shown in Fig. 4, can be developed mechanically

from a circle as follows: Starting with a point A at position O make a circle about a center C. Draw a horizontal line to the right of the circle from O to B and divide it into sixteen equal lengths. (For more accurate work, more divisions should be used.) This line represents the time it takes point A to go around the circle and is measured in degrees 0 to 360. Divide the circumference of the circle into the same number of divisions as there are in the horizontal line. A vertical line from each one of these division points on the cir-

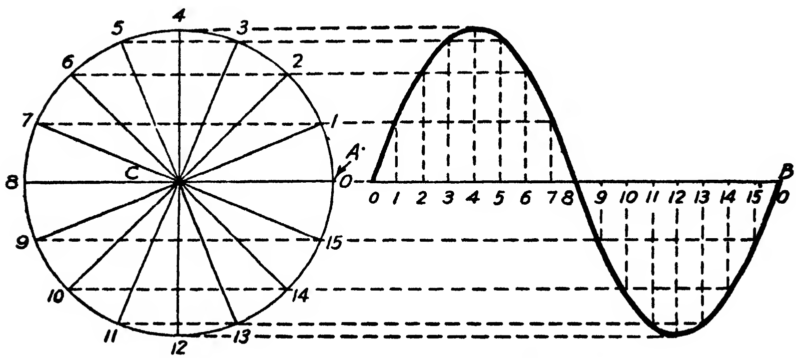


Fig. 4. Development of a Sine Curve from a Circle

cumference to the horizontal line through C represents the value of voltage generated at this particular instant by the coil in passing through the pole flux. These lengths laid off vertically on the horizontal line will give points through which the sine curve can be drawn, as shown in Fig. 4.

The voltage curves for generators do not conform to the sine wave usually pictured, but take shapes similar to those shown in Fig. 5. These shapes give better operating results and are used with practically all commercial machines. The shape of this voltage wave can be changed to any desired form by changing the contour of the pole face. In this figure the pole face is flat and the air gap uniform, which produces the wave form shown. If the pole face was changed slightly so as to weaken the flux density at the front and rear sides of the pole, the wave form would be more peaked and would look more like the sine wave. The wave form shown in Fig. 5 is made by a single coil in the armature slot. Commercial generators ordinarily have more than one coil per slot so the wave form is not quite so flat topped but is more like the sine curve.

PHASE

The term phase, as used in electrical work and in literature, has two separate and distinct meanings. Unless these are clearly and definitely understood a great deal of confusion may result. One

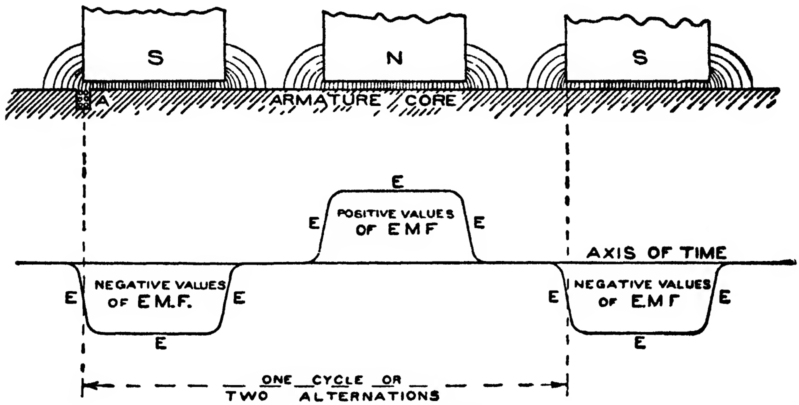


Fig 5 Development of Magnetic Fields and Voltage Curve Obtained from Them

meaning of the term phase has to do with circuits. Single-phase, two-phase, three-phase, and six-phase circuits are frequently mentioned in discussing alternating-current circuits.

A single-phase circuit may be defined as one which has voltage

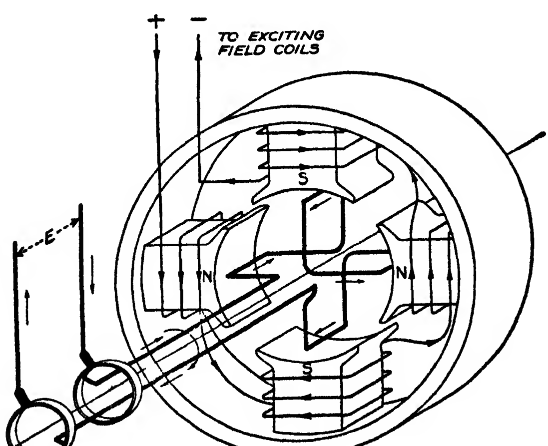


Fig. 6 A Single-Phase Alternator with a 4-Pole Revolving Armature. Phases are determined by windings and not by the number of poles

impressed upon it from only one alternating-current source. A single wire or coil revolving in a magnetic field will produce a single-phase circuit. The revolving coil shown in Fig. 3 would be a single-phase generator. The number of turns or the number of loops would

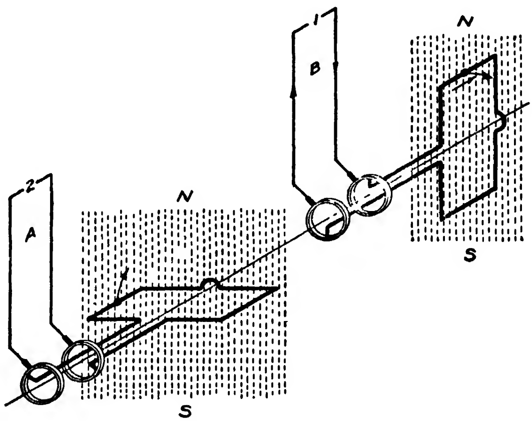


Fig. 7. Elementary Two-Phase Generator

not change the phases which are also independent of the number of poles as shown in Fig. 6. Although this machine has four poles and two loops, it is only a single-phase generator, as there is only one voltage wave acting on any circuit connected to the slip rings.

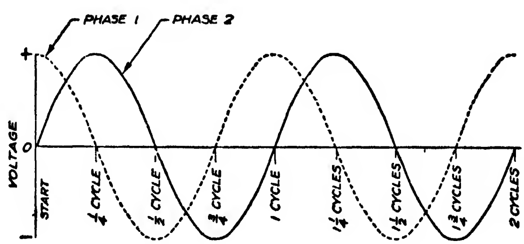


Fig. 8. Voltage Waves Generated by Two-Phase Generator—A Two-Phase Voltage Curve

A two-phase circuit in reality is two separate single-phase circuits, each with its own voltage wave impressed upon it. These two equal voltage waves are 90 degrees apart and always maintain this relationship. Fig. 7 shows a simple two-phase generator with the two separate windings 90 degrees apart rotating on the same shaft. This also shows the required two sets of slip rings and the

independent circuits 1 and 2 having absolutely no electrical connection with each other. The voltage waves produced by this generator are shown in Fig. 8. These are 90 degrees apart at the start and always maintain this relationship because the coils in the

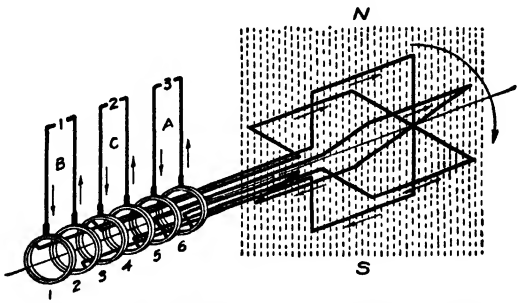


Fig. 9. Elementary Three-Phase Generator with All Six Leads Brought Out

generator generating the electromotive forces are set at the same angular displacement and cannot shift position.

A three-phase circuit is one in which three separate equal voltage waves are impressed 120 degrees apart on three circuit voltages. These may function on six wires but three wires ordinarily make a three-phase circuit. Fig. 9 illustrates a three-phase

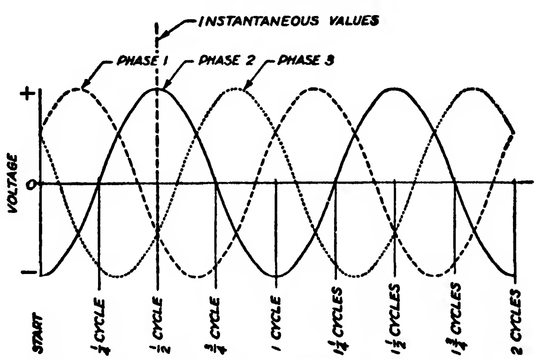


Fig. 10. Voltage Waves Generated by a Three-Phase Generator—A Three-Phase Voltage Curve

generator with all leads brought out to six-slip rings making a six-wire three-phase circuit. This is in reality three separate single-phase machines operating in the same magnetic field which makes all voltages equal. These circuits are often referred to as phases *A*, *B*, and *C* especially in line work and armature winding in order to

keep connections in correct order. The voltage waves shown in Fig. 10 show the relationship and position of the various voltages in a three-phase circuit. Because of the 120-degree spacing of the coils on this generator, all three voltage curves remain this same distance apart as shown in Fig. 10. A three-phase circuit has this particular characteristic. The instantaneous value of the voltage on one phase will be exactly equal to the algebraic sum of the voltages on the other two phases. Take the point where phases 1 and 3 cross below the line.

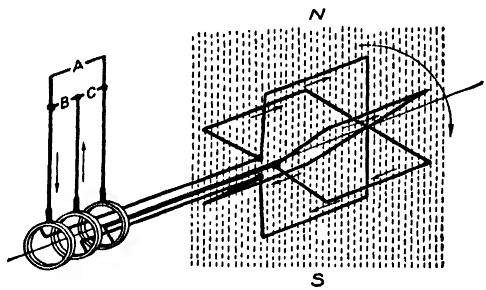


Fig. 11. Three-Phase Generator with Usual Internal Connections and Three Leads Brought Out

Measure this distance, and it will be found to be just half the distance to phase 2 above the line. This means that the sum of the two negative voltages on phases 1 and 3 will just equal the positive voltage on phase 2. All other points will give identical results at any position checked.

Because of this voltage condition on a three-phase circuit, the coils can be connected together inside the generator making only three slip rings necessary as shown in Fig. 11. This arrangement of coils enables each line to be a part of two phases as shown by *A*, *B*, and *C*, and each ring serves two coils in the generator which is standard in winding practice.

The other meaning of the term phase has to do with current and voltage relations within the circuit itself. When a load having ohmic resistance only is connected to a source of alternating-current voltage, the current wave will follow the voltage wave instantly, which means that current will be zero when the voltage is zero and reach a maximum value when the potential is at the peak, as shown by the curves in Fig. 12. The current and voltage are said to be ***in phase*** when this relationship exists.

A very few alternating-current electrical circuits have only ohmic resistance opposing the flow of current in them. Inductance or capacity, and in some cases both, are present along with the ohmic resistance to limit the flow. Inductive reactance is caused by the magnetic effects set up when alternating current flows in

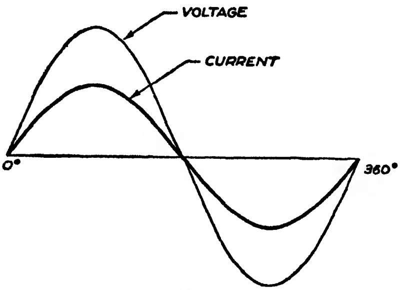


Fig 12 Voltage and Current in Phase in a Single-Phase Circuit

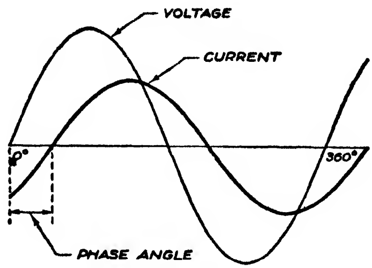


Fig 13 Voltage and Current Out of Phase in a Single-Phase Circuit

coils with an iron core such as are found in transformers, motors, and choke coils. This inductive effect from the alternating magnetic field acts like counter electromotive force on the flow of current and delays the time when it reaches a maximum value. Whenever this condition exists in a circuit, the current is said to be lagging behind the voltage and is *out of phase* as shown by Fig. 13. In this case the voltage and the current do not pass through zero or reach a maximum value at the same time. The current passes

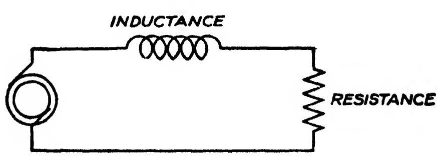


Fig 14 Choke Coil and Resistance in Single Phase Circuit Producing Effect Shown in Fig 13

through zero at a later time and reaches a maximum later than the voltage maximum. The angle between them, measured along the horizontal line between the points where the curves cross it, is called the *phase angle* between the current and the voltage. The cosine of this angle is the *power factor* for the circuit. Fig. 14 shows a choke coil in series with resistance connected to a source of alternating current producing the effect shown in Fig. 13. All three

types of opposition to current flow, whether it is ohmic, inductive, or capacity, are measured in ohms. These combine differently in an alternating-current circuit than the ohms of a direct-current circuit. Inductive ohms and capacity ohms act at right angles to the resistance in the circuit when both are present. Fig. 15 shows three conditions which may exist in an alternating-current circuit. In Fig. 15 at *A* is illustrated the relationship existing in a circuit of the type shown in Fig. 14. The three sides of the triangle are made from the following: the base *R* is the ohmic resistance, the

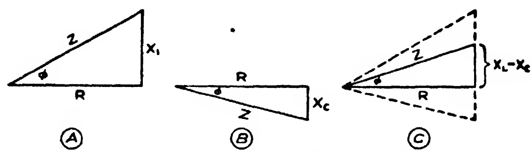


Fig 15 Triangular Relations of *A*—Resistance and Inductance, *B*—Resistance and Capacity, and *C*—Resistance, Inductance, and Capacity These control the current flow in an alternating current circuit

altitude X_L is the ohms reactance due to the magnetic effect, and the hypotenuse Z is the *impedance* or actual resistance to the flow of current in this circuit. In all mathematical calculations involving Ohm's law in alternating-current circuits, the current is obtained by dividing the volts applied to the circuit by the impedance. Impedance in each case must be found from the triangle developed in Fig. 15 at *A*, *B*, or *C* as the circuit conditions demand. In Fig. 15 *B* shows how capacity and resistance combine to control the current flow when capacity is present. *C* illustrates the combined effects on the impedance of a circuit having resistance, inductance, and reactance. The magnetic and capacity effects are 180 degrees apart and neutralize each other leaving only the difference to combine with resistance to form impedance. Because of this neutralizing action between capacity and induction, it is possible to change the power factor of any alternating-current circuit. On account of these magnetic effects, capacity in the form of static condensers or synchronous condensers is used to correct poor power factor.

The phase angle ϕ between the impedance and the resistance in Fig. 15 is the same as the angle between the current and the voltage in Fig. 13, because the current lag is caused by the same magnetic effect which determines the size of the angle ϕ in the triangle.

POWER FACTOR

Power factor is the ratio of true power to apparent power. It is the wattmeter reading divided by the apparent power. The apparent power is the product of the ammeter reading multiplied by the voltmeter reading. This division gives the power factor, because the triangle of real watts and apparent watts is similar to the impedance triangle shown in Fig. 15.

The power triangle shown in Fig. 16 is made from the volts and amperes which are the apparent watts in the circuit and the wattmeter reading. The magnetizing power may be measured with a

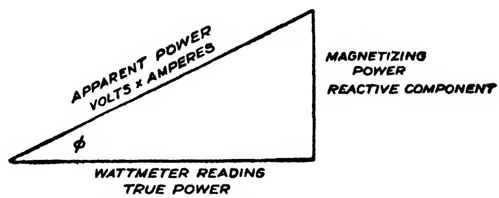


Fig. 16. Power Triangle of an Alternating-Current Circuit

reactive meter or may be calculated from the two previous sets of readings in the same way that the sides of any right-angled triangle may be found. Or the angle ϕ may be found from a table of cosines, as the wattmeter reading divided by the apparent watts gives the cosine ϕ. A protractor is used to lay off the angle and the magnetizing power is determined. This is a graphic method often used as a check on mathematical calculations. The reason these triangles are similar is due to the fact that inductance in an alternating-current circuit divides the current and voltage into two components, one acting on the resistance to produce useful work, and the other acting on the reactance to overcome the magnetic conditions in the circuit shown in Fig. 14.

TYPES OF WINDINGS

An alternating-current generator is a machine used to produce alternating current. It is made with three different types of windings to produce single-phase, two-phase, or three-phase current, depending upon what application is to be made of the power derived from the machine.

Direct current is almost always employed for exciting the

fields of alternating-current generators or synchronous motors. These direct-current exciters may be separately driven or mounted on same shaft as the alternator. Separately driven exciters are preferable, because they give more stable voltage conditions than the direct-connected machines. Exciters mounted on the same shaft with the main generator cause double the voltage variation with a change in speed as a separately driven unit, because an increase in speed will not only raise the alternator voltage but will increase the exciter current through the field. Thus a one per cent rise in speed

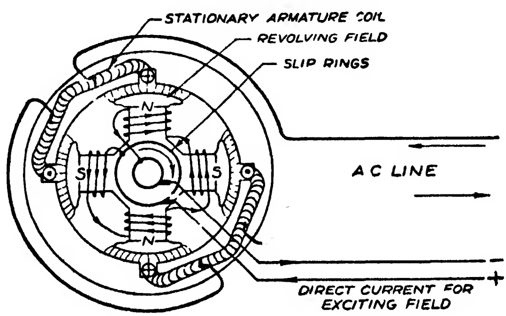


Fig 17 Single Phase 4 Pole Revolving Field Type of an Alternating Current Generator with Only One Group of Coils

will not only raise the alternator voltage one per cent but will at the same time increase the field one per cent which would make two per cent change on the main line voltage. Separately driven units are more flexible in a large plant as one exciter may be made to supply the field for one or more generators, or exciters may be operated in parallel with other direct-current machines doing the same service.

Single-Phase Alternator. As explained in the earlier pages of this lesson, a single-phase alternator is made with but a single winding in the part connected to the line and supplying power. The field may be made with any number of pairs of poles. Fig. 17 illustrates a single-phase, 4-pole, revolving field type of alternating-current generator. The moving parts of alternating-current machinery are nearly always referred to as the *rotor* while the stationary part is called the *stator*. The slip rings supplying the field are connected to some source of direct current. There is but a single set of coils on the stator and hence only one source of voltage which

makes this machine a single-phase alternator. In many cases a three-phase generator is so connected that two-thirds of the coils are used for a single-phase machine. This arrangement will permit the machine to deliver 65 per cent of its three-phase capacity.

Any machine operating as a single-phase alternator should be very carefully laminated throughout its magnetic circuit to reduce iron losses, and the pole shoes should have a heavy squirrel cage

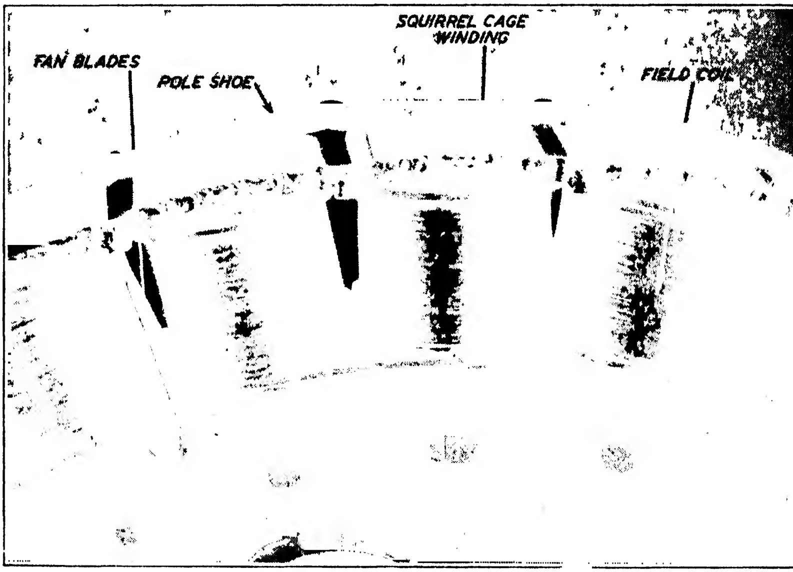


Fig. 18. A Partial Rotor Assembly Showing Method of Fastening Field Coils and Poles to Rotor
Courtesy of Electric Machinery and Manufacturing Company

winding provided to damp out the pulsating effects of the armature rotation. Fig. 18 shows a sectional view of a rotor with the squirrel cage winding in the pole shoe. These poles are assembled from their laminated punchings riveted together under hydraulic pressure. The squirrel cage or damper winding is welded on each side to insure a low resistance circuit completely around the rotor as this greatly increases the effectiveness of this type of winding.

For the same kilovolt amperes output, single-phase generators are fully 65 per cent heavier than a polyphase generator of the same power factor, speed, and voltage. This makes them not only more expensive to build, but increases all other investment costs.

Single-phase generators find application in electrochemical processes and some railway systems use single-phase power. Welding transformers and electrical furnaces use single-phase generators, so power sometimes has to be supplied for these particular applications where access to a power company line is not convenient. They also find some service in testing and experimental work.

Single-Phase Two-Wire System. The single-phase generator connected to a line gives the two-wire system as shown in Fig. 17. As alternator voltages are usually higher than secondary distribution voltages, a transformer is required between the generator and the load. The voltage used on a two-wire system is usually 110 volts and alternators generate 220, 440, 1300, 2300, 4000, 6600,

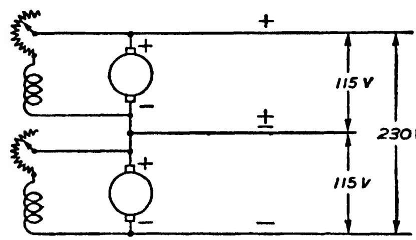


Fig. 19. Edison Direct-Current Three-Wire System

13,200 and a few 33,000 volts. The transformer ratio to produce 110 volts on the line will depend upon the voltage at the source.

Single-Phase Three-Wire System. The single-phase three-wire system has the same advantages for alternating-current systems as obtained with the three-wire direct-current systems discussed in Lesson 28. It is usually obtained on an alternating-current line by using a center tap on the secondary winding of the transformer. This method of obtaining the three-wire system has the added advantage of being able to handle any amount of unbalance there might be, whereas the balancer systems are definitely limited in ability to handle over a certain per cent of unequal load.

Edison System. The Edison three-wire system for direct current was originally developed and used by Thomas A. Edison. He connected two 2-wire generators in series and connected the middle wire to the center point of the two machines as shown in Fig. 19. This arrangement provided two voltages, one for light and the other for power and, at the same time, cut down transmission losses. Any

amount of unbalance in the load is taken care of without additional equipment. However, too much unbalance causes an excessive voltage on the side of the line with the smaller load. A similar system is used for alternating current from taps on transformer windings.

Two-Phase Alternator. The two-phase generator is exactly like the single-phase alternator except that it has two separate windings on the stator. These windings make two entirely separate electrical circuits which have no connection with each other. The second winding, phase two, is spaced exactly between the coils on the

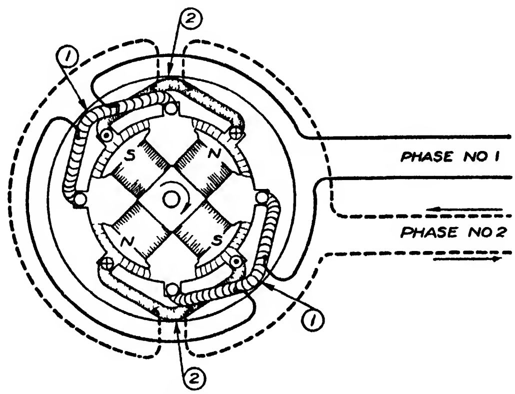


Fig 20. Two-Phase 4 Pole Revolving Field Type of an Alternating-Current Generator with Only Two Groups of Coils

generator in Fig. 17. With the poles in the position shown in this figure, the voltage on *phase 1* would be at a maximum as illustrated by the voltage at the start in Fig. 8. At this instant the voltage on *phase 2* is zero because the pole flux is not cutting the coils on this phase at this instant. The position of the poles one-eighth of a revolution later, Fig. 20, indicates that the voltage on *phase 2* is maximum and *phase 1* has decreased to zero. This condition is shown in Fig. 8 at point marked ¼ cycle. Because these curves are 90 electrical degrees apart and always remain in this relative position, the two-phase system is sometimes called the *quarter-phase* system, this being just one-fourth of a cycle which is 360 degrees.

Four-Wire System. An inspection of Fig. 20 shows four wires required to complete each of the circuits for the two phases. Whether these circuits are used for supplying power for lights or motors, they

are complete and independent throughout with the voltages remaining on the quarter-phase angle with reference to each other.

Three-Wire Two-Phase System. The two-phase four-wire system may be converted to a three-wire system by making one line wire common to both phases or circuits. In order for this wire to handle the currents in both phases, the area of copper must be approximately 41 per cent larger than either of the other two. The current caused by the common wire is exactly the square root of two which is 1.41 times the current in either outside line.

The principal reasons for developing polyphase systems was

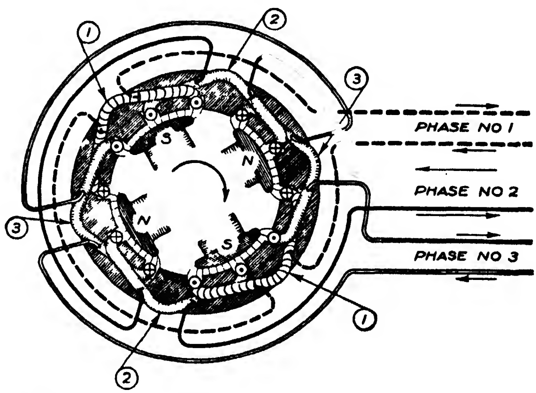


Fig 21. Three-Phase 4-Pole Revolving Field Type of an Alternating Current Generator with Only Three Groups of Coils

for the use of electric motors and savings in transmission costs. The early single-phase motor would run, but no means was known for developing torque for starting. Primarily, to meet this situation, two-phase systems were put into use. As soon as the three-phase circuit was discovered, its numerous advantages over a two-phase circuit made it so popular that very nearly all power systems changed over and the two-phase circuit has almost become history.

Three-Phase Alternator. The three-phase alternator is made by adding another phase to the two-phase machine. The addition of another set of coils makes a considerable difference in the voltage relations as will be seen from an inspection of the voltage curves shown in Fig. 10. The two-phase voltages were 90 degrees apart while these curves are separated by 120 degrees, which relationship is always maintained due to mechanical arrangement of stator coils.

This three-phase relationship is obtained by winding three sets of coils on the stator. They are practically always spaced 60 degrees apart, and one group is reversed so that the electromotive forces will be separated by 120 degrees. In Fig. 21 is shown a three-phase stator with the necessary three groups of coils. These are spaced exactly 60 degrees apart and all six ends brought out for each circuit. The pole position with reference to the different phases will give instantaneous voltages shown at the start of Fig. 10. The instantaneous voltage on phase two is at a maximum but is negative and is just starting toward zero, while the instantaneous voltages on phases one and three are both positive, but one is on the increase and three is already decreasing. This condition is explained from an inspection of Fig. 21. The two south poles are exactly under the coils in phase two producing a maximum negative voltage as shown by Fig. 10. The two north poles are partially over both phases one and three. As the rotor is revolving in a clockwise direction, the north poles are approaching phase one thus increasing the voltage positively, as shown in Fig. 10, and leaving phase three which causes a decrease in voltage as shown on the curve for phase three.

The leads to phase one have been reversed, which changes the voltage relations in the three phases from 60 degrees to 120 degrees. Windings for two- and three-phase stators are never wound, as shown in Figs. 20 and 21, this plan being used for simplicity in showing the phase relations. Factory windings for these machines would place sides of different coils in the same slot where the currents in the two sides would be in the same direction, as this arrangement gives more effective use of the iron. The diagrams become involved and difficult for the beginner to follow and understand the volutions in the various phases.

Six-Wire System. If all leads of the three-phase groups are brought out as shown in Fig. 21, six lines will be required and the system would be known as the six-wire system but would be only a three-phase system. This arrangement should not be confused with the conditions made by the windings of the ordinary three-phase alternator where six coil groups are used for each 360 magnetic degrees or pairs of poles. This coil arrangement would cause six different electromotive forces which would be 60 degrees apart or one-sixth of a cycle and would be known as a six-phase system.

If, however, the coil leads are connected either star or delta and three leads connected to the load, the resulting currents will differ in phase by 120 degrees. Thus an alternator may be either a three-phase or a six-phase machine depending upon the connections to the load.

Star-Connected-Four-Wire System. Figure 22 shows the coil groups in each phase connected together and the groups arranged at the 120-degree phase angle existing between each phase in the alternator shown in Fig. 21. Because of the fact that the instanta-

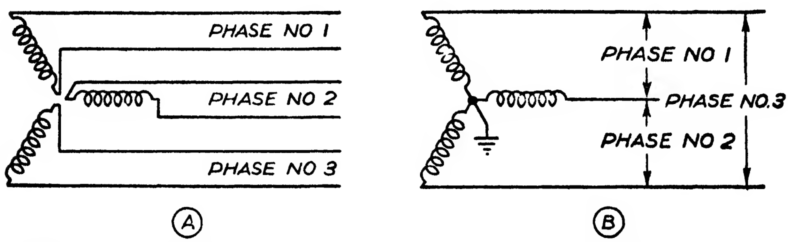


Fig 22 *A*—Schematic Diagram of a Three Phase Generator and a Six-Wire System; *B*—Three-Phase Generator Windings Y-Connected, Forming a Three-Wire System

neous value of voltage or current as shown by the curves in Fig. 10 is zero, each wire will act as a return for the other two. This makes possible the connection of the coil ends at the center of Fig. 22 at *A* which eliminates one wire from each phase and results in the wiring connection shown at *B*. A ground wire is frequently connected to the center tap and carried with the phase wires from the alternator through the whole distribution system. When this is done, the circuit is called the four-wire three-phase system.

The star connections of the coils, shown in Fig. 22 at *B*, places two groups of alternator coils in series for a one-line phase at the angle of 120 degrees. This results in a higher voltage on the line by the square root of 3 or 1.73 over the electromotive force obtained from one group of alternator coils with the connections as shown at *A*. Thus the alternator would have a higher voltage output but a more limited current output with this connection, no gain in power being accomplished.

The four-wire system of distribution permits an increased load on a three-wire line of nearly 75 per cent. Higher voltage transformers and motors may be used with resultant savings. Where this system has been tried, it has proved very satisfactory and ap-

parently no more hazardous with a good ground network than other grounded systems. A power company having a three-wire ungrounded system can, by increasing the generating capacity, changing the transformer connections, and using the fourth grounded wire, increase the total load on the lines practically 75 per cent.

Delta-Connected-Three-Wire System. Figure 23 shows the three coil groups for each phase in such a way that when they are joined

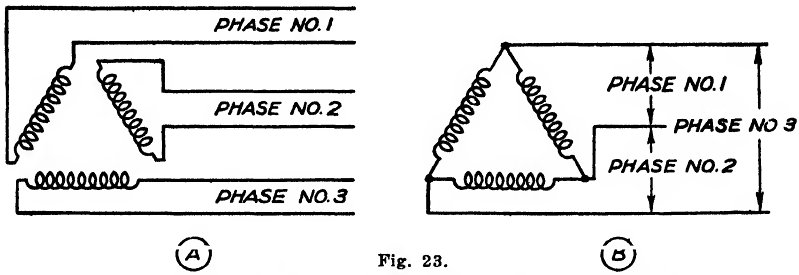


Fig. 23.
Three-Phase Delta Connection—Six Wires and Three Wires
A—Another Method of Showing a Three-Phase Generator Windings and a Six-Wire System; *B*—Three-Phase Generator Windings Delta-Connected, Forming a Three-Wire System

together they form a triangle or circular arrangement. Since there are 360 degrees in one cycle, this makes the three lines 120 degrees apart with reference to their phase relations. The delta connection gives the same voltage on each phase as the generator coil groups produce, but it increases the current delivered to the line by the square root of 3 or 1.73 due to the phase relationship.

The delta system is used extensively for transmission and distribution work. This connection is frequently used in winding induction motors as well as alternators. The power measured in kilovolt amperes is the same in an alternating-current generator regardless of the coil connection. With the star connection the voltage is higher by the square root of 3 and with the delta connection the current capacity is increased by the square root of 3 while the voltage remains at the single-phase value. Expressed mathematically, the power of the three phases of an alternator is: $P = EI \times \sqrt{3}$, where P is the power, E the voltage, and I the current for each phase as shown at *A*, Fig. 22. In the three-phase star-connected arrangement shown at *B*, Fig. 22, this becomes $P =$ (sq. root of 3) $\times E \times I$, where P is the three-phase power and E and I are the voltage and current the same as in the single-phase circuits. Power for the delta

connection is given by the formula $P=E \times$ (sq. root of 3) $\times I$ and applies to B, Fig. 23. Thus power is the same from an alternator regardless of which connection is used, but the star or Y connection delivers higher voltage to the transmission while the delta connection raises the amount of current which can be supplied, the voltage remaining the same as the single-phase potential.

CONSTRUCTION OF ALTERNATORS

Rating. The heating caused by the current in an alternator will determine its output. At normal voltage and normal current, a generator should not heat to a greater temperature than 40° C and should deliver its definite kilowatt rating at unity or 100 per cent power factor. Since the connected load determines the power factor at which the alternator must operate, its rating is usually given in kilovolt amperes, which is less than a kilowatt unless the power factor is unity. The rating if given in kilowatts is easily changed to kilovolt amperes by dividing the kilowatts by the power factor. A machine with a rating of 100 kilowatts would become a 125 kilovolt ampere rating at 80 per cent power factor. Ratings are frequently given in kilovolt amperes at 80 per cent power factor on the name plate of the machine.

Mechanical. Alternators may be made with revolving armature, where the generating coils rotate, or with rotating fields with the generating coils stationary. Practically all commercial machines use the latter construction while a few small alternators are built with moving coils. These require all the power current to be picked up with brushes on slip rings and more difficulty is experienced insulating the higher voltages found on the generating coils. Lighter moving parts cut down vibration with revolving field types and make machines with less weight per unit of output, all of which accounts for the preference shown for revolving field alternators.

The rotor or armature of the stationary field type of alternating-current generator is made by assembling laminations punched from special electric sheet steel. These punchings are varnished with special core varnish and assembled under pressure on a cast or steel spider to which they are securely fastened. Spaces are left when assembling to permit free circulation of cooling air. The coils on lower voltage armatures are wound with double-cotton or single-

cotton enamel magnet wire. These are then taped with cotton and oil linen tape, treated with waterproof and oilproof baking varnish, and dried in an oven at controlled temperatures. Slot insulation is made from a combination of insulating paper and varnished cloth.

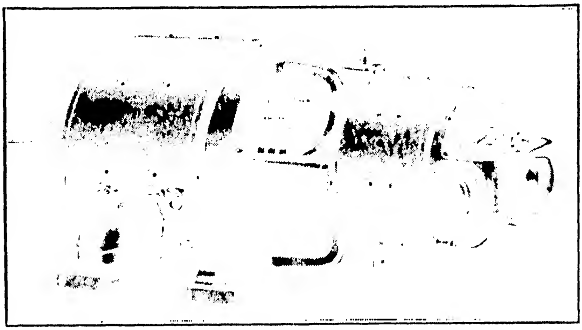


Fig. 24. An Alternating Current Generator with a Direct-Connected Exciter
Courtesy of Imperial Electric Company

The coils are held in the slots with wood or fiber wedges which fit into dovetails in the teeth of the rotor.

The collector rings for revolving coil armatures are made of special bronze in order to improve wearing qualities and have low contact drop at the brushes. These rings must be thoroughly insulated from the rotor spider and yet be securely fastened to it. Fig. 24 shows an alternating-current unit made in capacities from

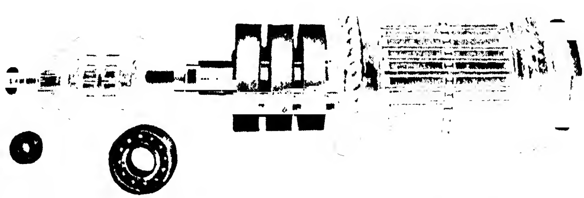


Fig 25 Alternating-Current Winding on Rotor of Alternator (Right) and Direct Current Armature of Exciter (Left) Mounted on Same Shaft
Courtesy of Troy Engine and Machine Company

1 to 150 kilovolt amperes with an exciter unit mounted on the main shaft. Fig. 25 shows the rotor element with the direct-connected exciter unit. Note the heavy-duty slip rings and the wedges holding the coils securely in the slots.

Armature Windings. The most important of several factors

which affect the arrangement of the windings used on an alternator are: (1) wave shape; (2) coil distribution; (3) winding costs; and (4) efficient generation of voltage. Some other features, such as number of poles and frequency, will be determined by the speed to be used, and will also have their effects on the armature windings.

The wave shape should approximate the sine wave, which would mean coil distribution up to certain limits. In order to obtain the required distribution to produce the desired wave shape, the coils must occupy several slots per pole per phase. These may be a whole number, but it is not necessary as 1½ slots per pole per phase may give a satisfactory wave form. Wave form is also frequently improved by using a fractional pitch winding. A fractional pitch winding is one which spans fewer slots than the pole covers which would make the coil sides somewhat less than 180 electrical degrees apart. This sometimes is reduced to .66 and even .5.

Distribution of windings makes better ventilation possible and helps reduce leakage reactance as well as improve the wave shape. However this is limited, particularly on high voltage machines, as more insulation must be used between layers in slots and less room is available for copper. End turns must also be more carefully insulated.

The cost of winding is an important item for consideration in constructing an alternator. Coils which can be formed and insulated before being placed in the slots very materially reduce costs and are better insulated. Form wound coils should all be the same shape. They require that the slots be open at the top, which reduces the efficiency of operation of the machine. However, these open slots may be closed or partially closed with magnetic wedges.

Efficient generation of voltage requires that the winding must be arranged so there is very little bucking action present. To avoid this trouble, the coils must be very nearly full pitch, that is, the sides must be approximately 180 degrees apart magnetically.

A careful analysis of the foregoing facts indicates that satisfactory winding of a machine will depend upon what is desired in the way of operating requirements such as wave form, efficiency and regulation as well as the first cost involved. Where conflicting variables occur, a compromise must be made which best meets the requirements. If the alternator is wound with three-phase windings,

these may be star- or delta-connected. In many cases there may be two independent groups of coils for each phase, especially with motor windings. Two sets of coils per phase make the machine easily converted into double normal voltage. A 220-volt connection can be made into a 440-volt winding by simply putting the groups in series.

Figure 26 shows a winding diagram for an alternator having 18

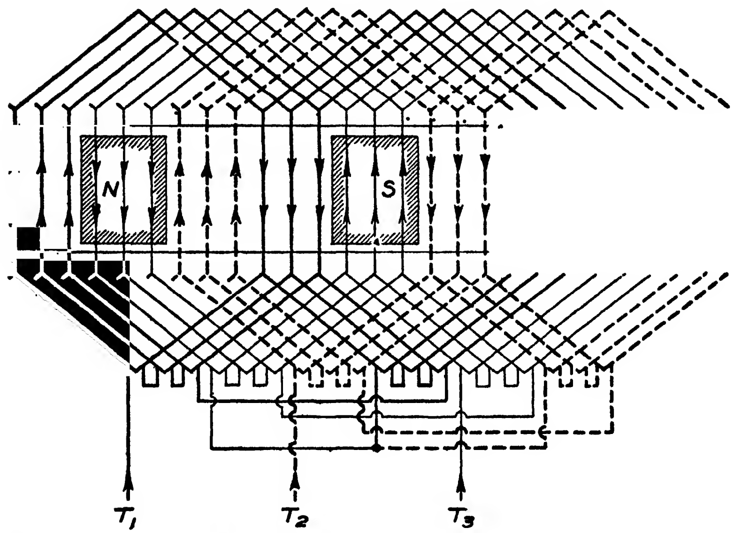


Fig. 26. Three-Phase Alternator Winding with 18 Slots, 18 Coils, 2-Pole Star-Connected

slots with 18 coils two-pole star-connected. This makes 6 coils per phase and 3 coils per pole per phase. The pitch is full being 1 and 10. Phase 1 is shown in light lines, phase two in heavy lines, and phase three in broken lines. This is a very simple connection and is shown to give the idea of the winding layout. In practice more coils would be used and the coils would be placed with sides of different coils in the same slot, as current directions are such in three phase as to permit this practice.

REVOLVING FIELD ALTERNATOR

The revolving field alternator is built in all types including the belt-driven, high-speed direct-connected steam engine, slow-speed type, Diesel engine, turbo-generator, and the water-wheel type.

Figure 27 shows a high-speed alternating-current generator made with either two or three bearings for belt drive or with one or two bearings where it is coupled to the prime mover. This unit is designed especially for use with oil, gas, or steam engine and built in capacities ranging from 12½ to 1250 kilovolt amperes 60-cycle with speeds from 514 to 1800 r.p.m. Note the open frame construction with the ducts at frequent intervals in the stator laminations. The air enters the machine through the end brackets, passes over the stator and field coils as well as through the stator core. This is accom-

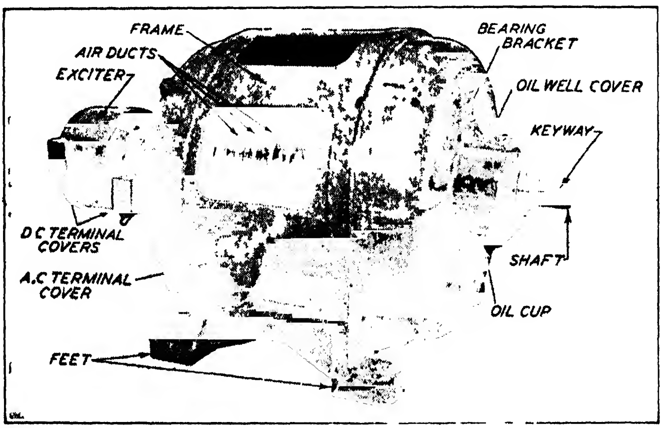


Fig. 27. Westinghouse Type G Alternating Current Generator with Exciter Mounted on End of Generator

plished by an ample system of ducts and baffles which prevents recirculation of the heated air. A sealed type of sleeve bearing, made oil, vapor, and dust tight, reduces bearing wear to a negligible amount.

Stator. The stator frame of this machine is made of grey cast iron with the feet cast integral with the frame. The modern trend in all frame construction is toward rolled and welded steel frame construction. The core is built up with high-grade annealed steel sheet punchings dovetailed into transverse ribs in the frame. These laminations are compressed between end rings and keyed in place.

The coils are form wound from double cotton covered wire with the slot portions wrapped with fish paper and mica. This insulation is not affected by heat or moisture, and age has very little deleterious or harmful effect on its insulating qualities. Every stator is given a radio frequency test which indicates insulation defects on

individual turns. In this way the factory knows that each machine is free from defective coils. This defeats the chief cause of electrical breakdowns. Fig. 28 shows the high-frequency test being given to a large stator in process of construction.

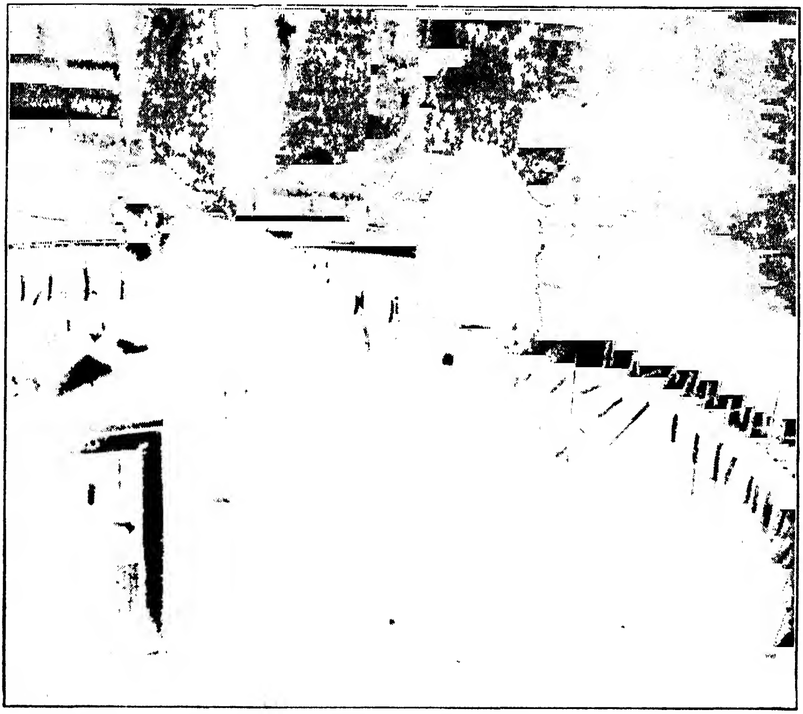


Fig. 28. Testing Alternating Current Windings with High-Frequency Alternating Current
Courtesy of Electric Machinery and Manufacturing Company

Rotor. The spider of the rotor is built up with steel punchings riveted together under hydraulic pressure. This core is then pressed and keyed to a steel axle shaft or a forged flange steel shaft for single bearing machines. The pole pieces are assembled from the electrical steel laminations riveted together under pressure. These poles are tightly dovetailed into rotor spider and keyed in position. The whole shaft and rotor is made with ample strength to withstand the variations in angular toraue produced by Diesel engines.

The field coils are wound with copper straps or rectangular double cotton covered wire. As these are wound, an application of

insulating varnish is made to each layer and the whole coil is then impregnated with heat-resisting compound. Each coil is carefully insulated from the core and supports are provided to protect the coils against centrifugal forces and strains during operation. Fig. 29 shows a rotor used with the larger machines of this type. Note the damper winding provided near the pole faces to minimize hunting and variations in speed of certain types of prime movers. This addition to the rotor winding is almost a necessity where gas or

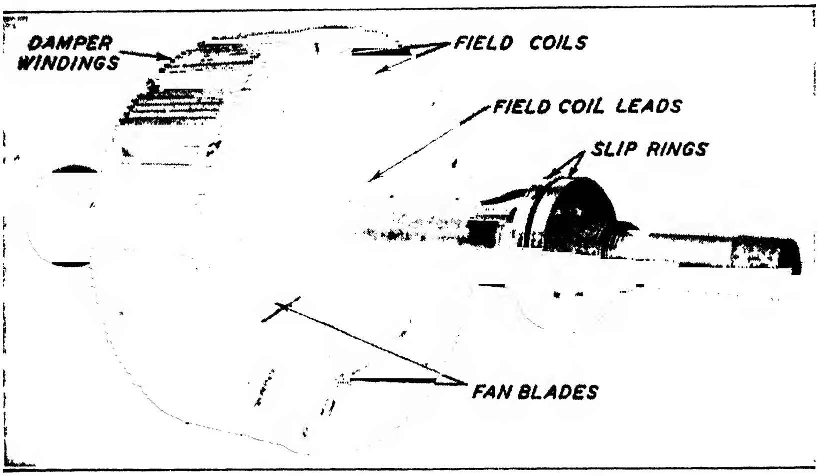


Fig 29 Field Winding Mounted on the Rotor of a Large Alternator
Courtesy of Westinghouse Electric and Manufacturing Company

Diesel engines are used for motive power. Cast-iron collector rings are used almost exclusively on rotors magnetized from a direct-current source.

Exciters for these alternators are usually mounted directly to the frame of the generator with the exciter armature mounted on an extension of the rotor shaft. This eliminates the necessity for exciter bearings. In applications where direct-connected exciters are not desirable, any method of drive may be resorted to. Dual drive is frequently used in larger power houses with motor drive a highly favored method Gas, steam engine, turbo, and water-wheel units are frequently used to power exciters. There are a few installations where V-belts are used from the main alternator shaft to the exciter.

SLOW-SPEED ENGINE-DRIVEN GENERATORS

The slow-speed generator is from necessity a massive piece of equipment with large weight per kilovolt amperes of output. Slow-speed machines require a larger number of poles to produce a given

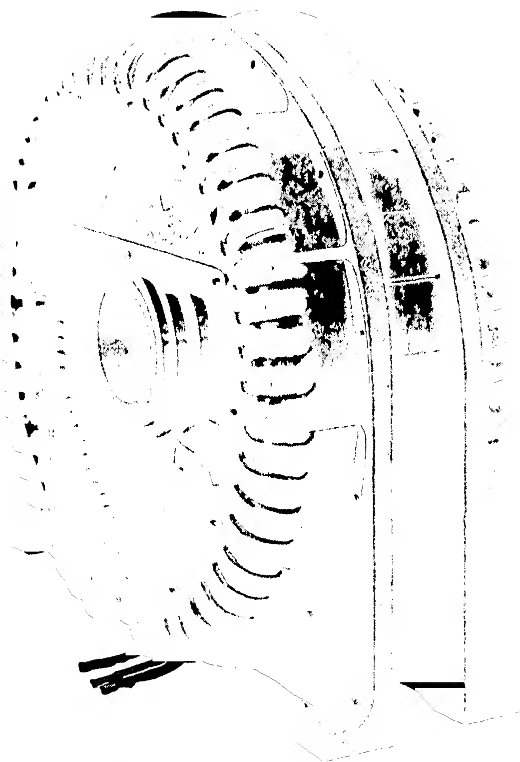


Fig 30 Engine Driven Type of Alternator The Shaft and Bearings are Built as Part of the Engine
Courtesy of General Electric Company

frequency than is required with high-speed machines. In order to accommodate a large number of poles, the rotor diameter must be increased over what is required in more rapid moving elements. With slow moving field poles, larger sizes must be provided to furnish the magnetic flux necessary to generate the proper voltage. This leads to longer stator coils with increased iron in the stator.

Figure 30 gives an excellent idea of a slow-speed alternating-

current generator used in direct connection to a steam or Diesel engine. The open style frame provides ample opportunity for good ventilation. The end shields are die formed and thoroughly protect the windings without interfering with air circulation over the stator coils. A pole piece for this generator is shown in Fig. 31. The damper windings are located in the slots in the face of this pole piece. The cores for these poles are assembled in the same manner

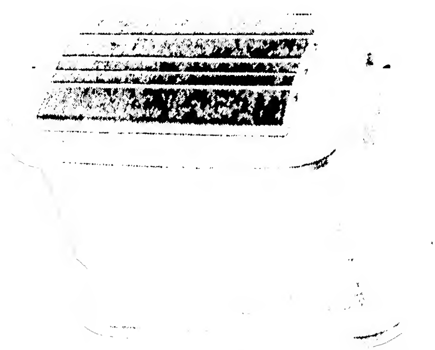


Fig. 31. The Pole of a Slow-Speed Engine Type Generator
Courtesy of General Electric Company

as other field poles but are drilled and tapped for pole bolts. These poles are slightly spiraled on the rotor spider in order to reduce magnetic hum when the machine is carrying load. The field coils are wound with rectangular double cotton covered wire, as this shape increases the copper area of the coil. The usual treatment is given the coil to properly insulate it.

These rotors are supplied with or without damper windings depending upon the operating requirements the machine must meet. When these are supplied, they are made from either brass or copper bars embedded in the slots of the pole face, fitted into holes in the end rings and silver soldered under red heat. The silver solder forms a strong low resistance connection and has exceptional penetrating qualities. To facilitate pole removal, the end rings are made in sections.

DIESEL ENGINE GENERATORS

The Diesel Engine generator is of the slow-speed heavy construction type similar to the machine just previously discussed. Due to the more recent development of alternators for this type of drive,

the frame construction is nearly all fabricated, rolled and welded. The speeds of these machines very closely parallel those for the slow-speed engine type ranging from 257 to 450 r.p.m. Somewhat more rigidity must be put into the rotor shaft on account of the tendency

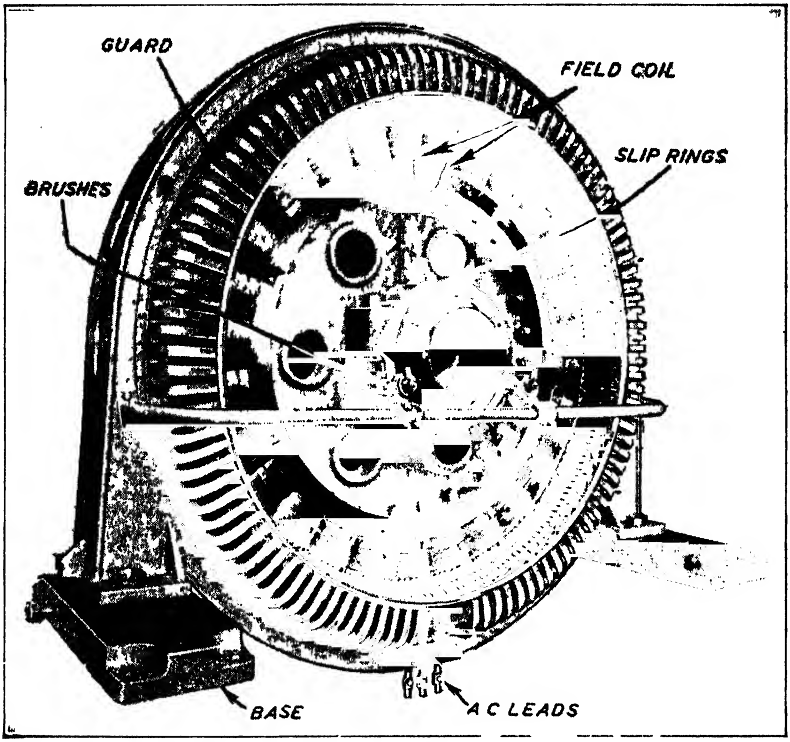


Fig 32 A Large Slow Speed Alternator to be Driven by a Diesel Engine
Courtesy of Electric Machinery and Manufacturing Company

of Diesel engines producing oscillating torque effects. Heavier damper windings are used on the poles to aid in smoothing out the engine torque when alternators are constructed especially for this prime mover. Fig 32 shows a fabricated frame alternator built to operate with Diesel engine drive. Note the extremely heavy rotor flange to which the poles are bolted. The additional flywheel effect secured with this material is an aid to smoother operation of the unit. Even with the heaviest rotors, additional material is required to keep down the hunting tendencies of Diesel driven alternators. A heavy flywheel is usually provided

for this purpose. Fig. 33 shows a modern Diesel direct connected to an alternator with the stabilizing flywheel. Reciprocating steam engine driven generators have this same hunting tendency, but it is more pronounced in the Diesel so that heavier flywheels are required than are ordinarily used with steam units.

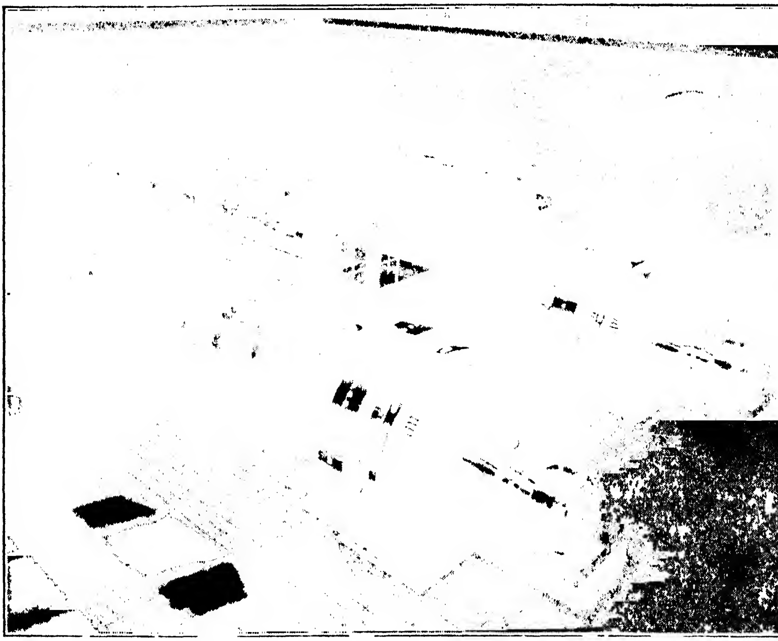


Fig 33 A Diesel Engine Plant Consisting of Two Alternators with Direct Connected Exciters
Courtesy of Electric Machinery and Manufacturing Company

ALTERNATING-CURRENT GENERATORS AND MOTORS

FOREWORD

The alternating-current system of power generation and distribution has been almost universally adopted since the invention of the transformer and the induction motor. The transformer has made possible the transmission of power over great distances with relatively low losses at high voltages and ready step-down to usable voltages at the point of use. The relative simplicity of alternating-current machines, both generators and motors, allows them to be produced at less cost than that of direct-current machines. In addition to the advantage of lower purchase price, alternating-current machines, because of their reduced number of parts, cost less to maintain.

FREQUENCY OF ALTERNATING-CURRENT SYSTEMS

In the early days of power-distribution systems and the manufacture of electric machines, a number of frequencies came into use because of lack of standardization and differences of opinion as to the best frequency from the standpoint of design. Consequently, frequencies of 25, 30, 40, 50, and 60 were used. Proponents of each system felt that certain advantages outweighed the advantages of standardization.

Design difficulties in machines of higher frequency were overcome as engineering and manufacturing technique advanced and the advantages of higher frequency became obvious. Since high frequency eliminates visible pulsation, thus improving lighting service, 60-cycle systems have become standard in the United States. The few remaining systems of lower frequency are rapidly being converted to 60 cycles to allow interconnection without the necessity of expensive frequency-changer sets at interconnecting points.

Therefore, purchasers of power will find 60-cycle systems available in practically every part of the United States. Anyone consider-

Photographs appearing throughout this section are by courtesy of General Electric Company.

ing the installation of an isolated generating plant should plan to use the 60-cycle system. The relatively greater availability of 60-cycle apparatus and devices, at lower cost, and the possibility of parallel or stand-by operation with purchased power warrants such a decision.

TYPES OF ALTERNATING-CURRENT SYSTEMS

Power will be derived from the incoming circuit of a power-distribution company or from one or more plant generators.

Single-Phase Type. The use of single-phase generators for general power is so infrequent that its principle will not be discussed here.

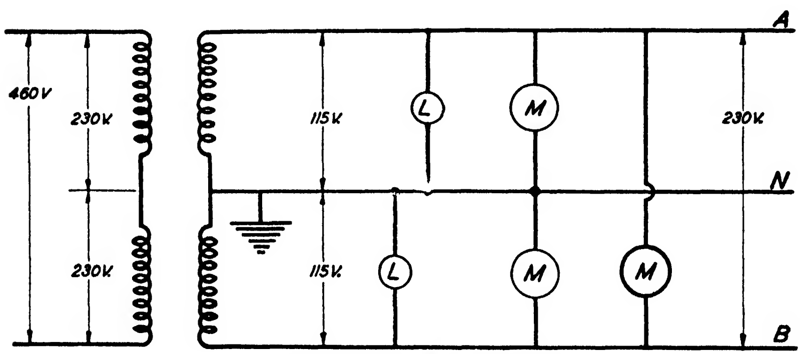


Fig. 1 Single-Phase, Three-Wire System

However, the derivation of single-phase circuits from a power-distribution system for lighting and for small motor loads is common. Single-phase generators are not used for large concentrations of power load, but may be used on small motor loads where the cost of running three-phase feeders to the motors would more than offset the higher cost of single-phase motors and slight added capacity in the single-phase line above requirements for lighting only.

Fig. 1 illustrates the use of an insulating-type, single-phase transformer with multiple primary and secondary windings in producing a 115/230 volt, three-wire system for lighting distribution. The same transformer with its primary coils in parallel may be connected across 230 volts, two-wire, to produce 115/230 volts, three-wire, on the secondary. As shown, lights and small motors are connected across 115 volts, and motors may be connected across 230 volts. Phase wires A and B need be large enough to carry the rated

output of the transformer, $I = \frac{kva}{V}$. Neutral wire N need be only large enough to carry the unbalance in load between two halves of

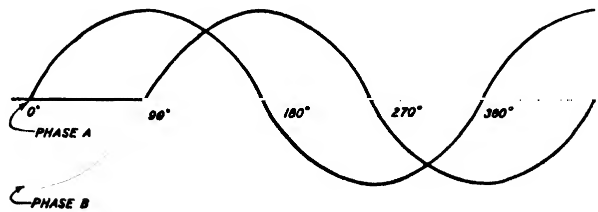


Fig 2 Voltage Curves for Two-Phase Alternator

the three-wire system. The load between two halves should be divided as evenly as possible. In no instance should unbalance be such as to produce current in N in excess of 10 per cent of line current in A and B. Otherwise, neither the transformer nor line capacity will be utilized efficiently.

Two-Phase Type. Although gradually being replaced by three-phase systems, there are a number of two-phase distribution systems in use in this country. Two-phase may be derived directly from generator terminals or by transformation from a three-phase system to supply existing two-phase distribution systems.

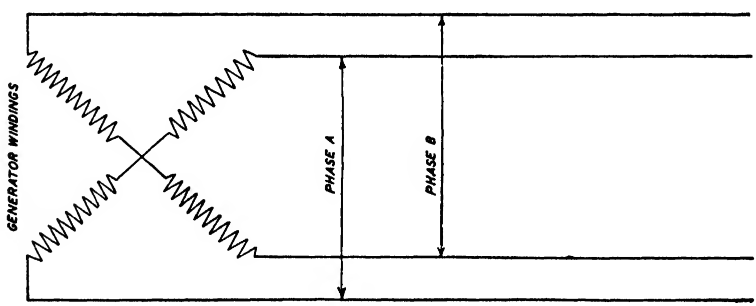


Fig 3 Wiring Diagram for Two-Phase, Four-Wire Generator with Armature Windings 90 Degrees Apart

A two-phase alternator has two separate armature windings so placed that the voltage generated in each winding is displaced 90 degrees out of phase with the other. Fig. 2 shows the two voltages plotted with one-phase voltage leading the other by 90 electrical degrees. Since there are 360 degrees per cycle, one phase leads by

one-quarter cycle and, therefore, such units are sometimes called quarter-phase generators.

Fig. 3 shows the winding of a two-phase, four-wire generator. Voltages of phases A and B are equal. If the windings are connected so that one conductor of each phase is common, as shown in Fig. 4, we have a two-phase, three-wire system. When the mid-points of both windings of a quarter-phase generator are tied together, as on some machines, this system cannot be used. If the voltage of either phase is equal to E, then the voltage across the free ends of the interconnected phase will be equal to $E\sqrt{2}$.

In the vector diagram shown in Fig. 4, the two lines which repre-

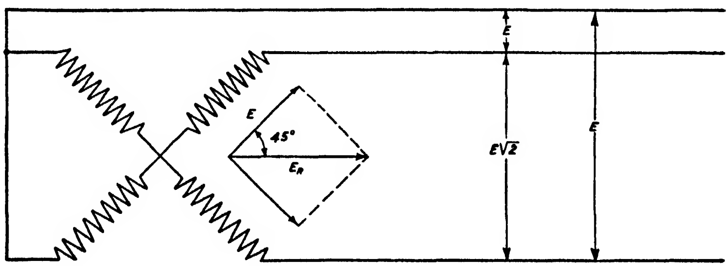


Fig. 4. Wiring Diagram for Two-Phase Generator Arranged for Three-Wire System

sent the voltages E are 90 degrees apart and form a right angle. A square can be formed by drawing the two dotted lines parallel to the lines E. In finding the length of the diagonal line, it is necessary to apply the law of the right triangle, which is as follows: The hypotenuse of a right-angle triangle is equal to the square root of the sum of the squares of the two sides adjacent to the right angle. Then considering the value of E to be 1, the value of E_R is equal to the square root of $1^2+1^2=\sqrt{1+1}=\sqrt{2}$ which is 1.414. Therefore, $E_R=E\sqrt{2}$.

The current in any wire of a two-phase, four-wire system is

$$I=\frac{kw}{2E}$$

in which kw is capacity of generator; E, voltage of phase A or B. The current in the common or neutral conductor of a two-phase, three-wire system is $\sqrt{2}$ or 1.414 times the current in the other conductors with balanced load.

If it is desired to produce a two-phase, four-wire circuit from a three-phase, three-wire system, Scott-connected transformers may be used, as shown in Fig. 5. In a two-phase system, since the phase

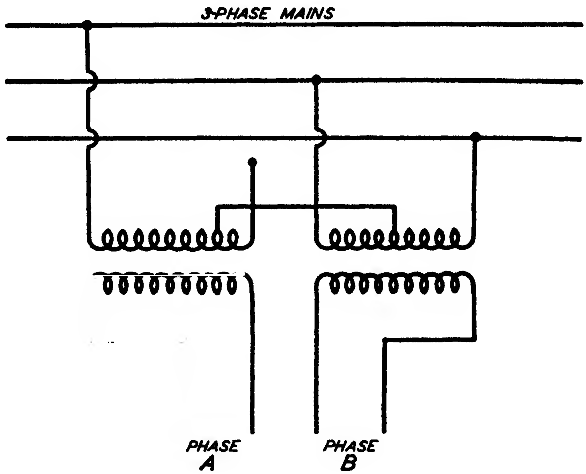


Fig. 5. Three-Phase to Two-Phase Transformation by Scott Connection of Transformers

voltage is generally 230 volts or 460 volts, a lighting circuit is obtained by use of a single-phase 115/230 volt, secondary-winding transformer.

Three-Phase Type. Three-phase generators have their armature windings divided into three sets of coils so arranged as to produce

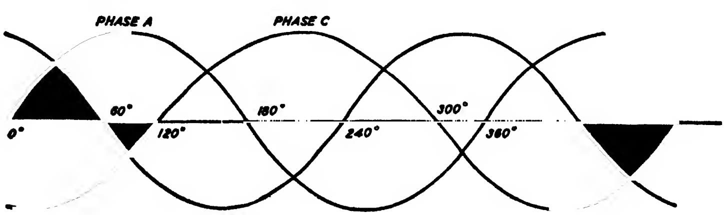


Fig 6 Voltage Curves for Three-Phase Generator

electromotive forces 120 degrees apart, Fig. 6. Armatures may be either Y- or Δ-connected, Figs. 7 and 8. In a Y-connected system the line voltage E_R is greater than the voltage produced by that particular phase-winding, as is shown by the vector diagram in Fig. 7. By the use of trigonometry, the line voltage E_R has been found to be

equal to the phase voltage times the square root of 3 or 1.732 E. The current in each line wire is the same as the current in each phase winding.

In a Δ-connected system, the line voltage is the same as the phase

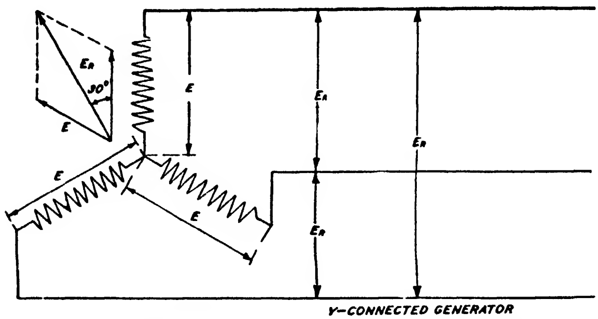


Fig 7 Wiring Diagram for Y-Connected Three-Phase Generator

voltage, but the current per line is the $\sqrt{3}$ times the current per phase. In either system, star (Y) or delta (Δ)

$$W = EI\sqrt{3}$$

for a noninductive circuit, in which W is watts output, E is pressure in volts, and I is current in amperes.

For an inductive circuit whose power factor is less than unity

$$W = EI\sqrt{3}\cos\theta$$

in which $\cos\theta$ is power factor.

When using transformers, a three-phase, three-wire circuit may be produced by use of two single-phase transformers with secondaries

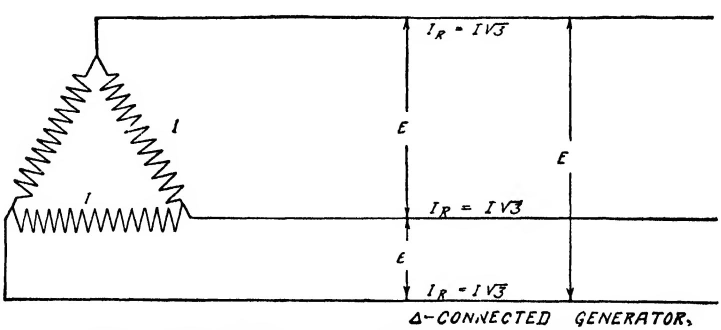


Fig 8 Wiring Diagram for Δ-Connected Three-Phase Generator

connected in open delta. This allows minimum first cost with the possibility of adding a third single-phase transformer at a later date, if load builds up to demand it.

A major development in recent years is the three-phase, four-wire system of secondary distribution for buildings and manufacturing plants. Where large blocks of power are generated and distributed, it is common practice to ground the neutral or common point in a Y-connected generator or transformer, thereby creating a three-phase, four-wire system. This allows transmission at a voltage

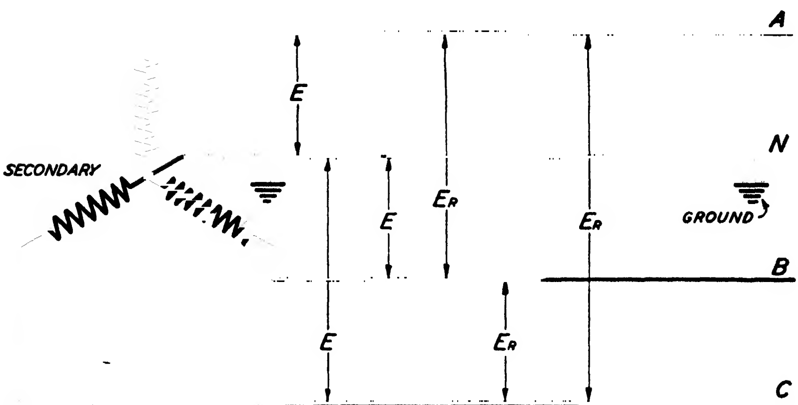


Fig 9 Three-Phase Four-Wire Distribution from Three Transformers The Neutral Is Grounded

$\sqrt{3}$ (1.73) times the phase voltage of the generator or transformer windings, resulting in less copper loss and making possible the use of lower priced cable.

The most common voltage used on this system is 120/208 volts, Y-connected. It is derived from secondaries of three single-phase transformers with 120-volt secondary windings, Y connected, as shown in Fig. 9. In this system, the voltage from each phase to neutral $= E$ or 120 volts, and the line voltage, phase to phase, $E_R = \sqrt{3} \times E$ or 208 volts.

In practice, the three phase conductors and the neutral conductors are carried throughout the plant or building, the three phase lines being connected to 208-volt, three-phase motors. One or more phase wires and the neutral are used for lighting requirements. Connection from phase to neutral allows 120 volts for lighting and for

small motors, without the need of adding transformers to provide lighting circuits. The lighting load is evenly divided between phases and neutral so that the neutral conductor need be only large enough to carry the unbalance, never greater than 10 per cent.

System Voltages. The most commonly used distribution systems are at 4,000, 2,300, 460, or 240 volts, all three-phase, three-wire, and 120/208 volts, three-phase, four-wire circuits. Voltage selection depends on many factors including kilowatts of load to be distributed and distance to be transmitted. If a 2,300 or 4,000 volt distribution system is used, it is necessary to install step-down transformers at points of use of smaller motors and of lighting. This reduces the copper losses and permits use of smaller sizes of cable. A similar reduction is necessary for lighting purposes when a 460 or 230-volt system is used.

Small plants and buildings may be served by 460 or 230-volt, three-phase, three-wire circuits to motors with separate 115/230-volt lighting system, or by 120/208-volt Y three-phase, four-wire system. Generators can be selected to generate at any one of these voltages. The circuit can also be derived from step-down transformers.

Selection of a Distribution System. Unless some special consideration incident to existing equipment is required, the system selected should be 60-cycle, three-phase, and either 460/230 volt, three-wire, or 120/208 volt (Y), three-phase, four-wire. The final selection can be made only after a thorough study of all costs involved for a particular plant or building.

SELECTION OF GENERATORS

Modern alternating-current generators, sometimes called alternators, are constructed with a stationary armature or stator wound to produce single-phase, two-phase, or three-phase voltage, and a revolving field or rotor excited from a separate 125- or 230-volt direct-current source. Machines up to 1,200 r.p.m. have their field coils protruding from the rotor and are called the salient-pole type. See Figs. 10 and 11. On turbine type generators operating up to 3,600 r.p.m., the field coils are imbedded in slots of a cylindrical steel rotor to reduce noise and wind friction and to provide necessary strength for operation at high speed. The exciting current is brought to the revolving field through stationary brushes which run on

collector rings mounted on and insulated from the shaft. The terminals of the field winding are brought to these rings. In most instances, especially on generators 600 r.p.m. and above, the exciter is direct-connected to the generator shaft. The formula,

$$f=\frac{P}{2}\times\frac{\text{r.p.m.}}{60} \tag{1}$$

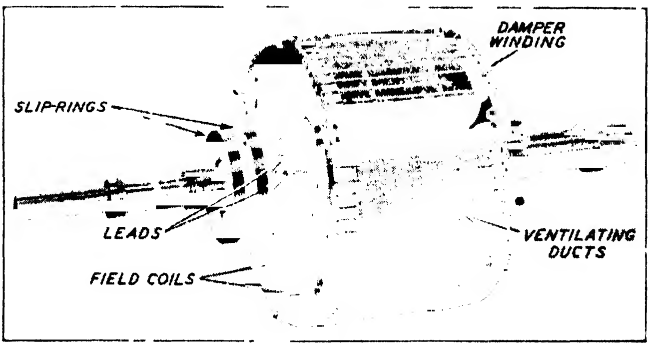


Fig. 10 Revolving Field for 250 Kva (150 Kw), 60 Per Cent Power Factor, 1,200 R p m Generator

where

f = cycles per second (frequency)
P = number of poles (always an even number—2, 4, 6, etc.)
r.p.m. = revolutions per minute

determines the fundamental characteristics of all alternating-current machines, both generators and motors. Therefore, after the frequency of the system is known, the operating speed may be determined. Where frequency is, let us say, 60 cycles, the maximum synchronous speed of the machine will be 3,600 r.p.m., and so on down to 1,800, 1,200, 900, 720, 600 r.p.m., and so forth.

Let us assume that it has been decided to generate all or part of the power required in a particular plant or building. The most important problem at this point is to determine the size of the generating unit or units required. Generators are rated in kilovolt-amperes at 0.8 power factor or the resulting kilowatts—for example, 250 kva at 0.8 power factor or 200 kw—since it may be assumed that the average inductive load of motors will be 0.8 power factor, lagging or higher.

Generators are designed with fields and exciters of sufficient capacity to produce leading kva to offset the lagging kva of inductive loads and are sometimes rated 0.7 and 0.6 power factor or lower for special conditions.

Typical generators of small and medium size are rated as standard 125, 156, 187, 219, 250, 312, 375, 438, 500 kva and so forth, up to 1,000 kva in standardized steps. Standard ratings are based on 50°C. rise on the armature for continuous loading at rated kva.

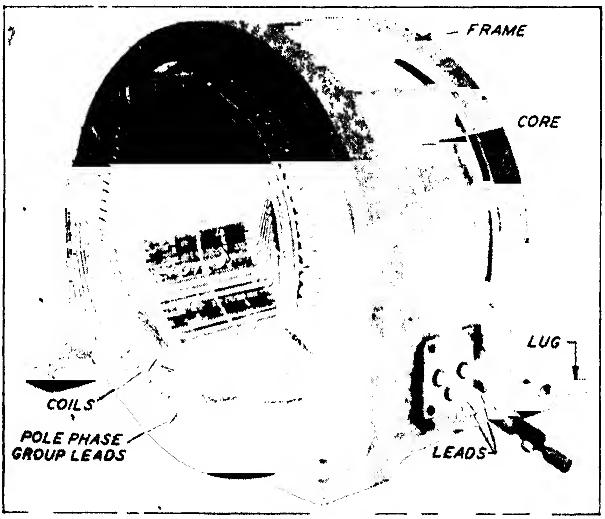


Fig 11 Stator for 250 Kva (150 Kw), 60 Per Cent Power Factor, 1,200 R p m Generator

Such generators are nominally rated machines. For special loading conditions, requiring overload for definite periods, a special rating may be purchased—for example, rated load 40°C. rise continuous, 25 per cent overload two hours, 55°C rise; or rated load 50°C. rise continuous, 10 per cent overload, two hours. The last-mentioned rating is standard for generators driven by Diesel engines.

The nature of the load will be taken into consideration when selecting the size of generating units. Only in rare instances will the load be constant over the entire operating period. It is probable that there will be an established minimum, for example, 200 kw, above which the load will increase during peaks. If, then, we establish 200 kw as the *base* load, we may pick a generator of that capacity

as the *base* generating unit, with additional unit or units to carry added load to peak requirements.

Since no generating unit can be considered indefatigable, it is necessary to plan for stand-by or spare generating capacity against the time when each unit must be taken out of service for periodic overhauling or repair. In anticipation of such times, the size of units for stand-by or peak requirements should be such that one or

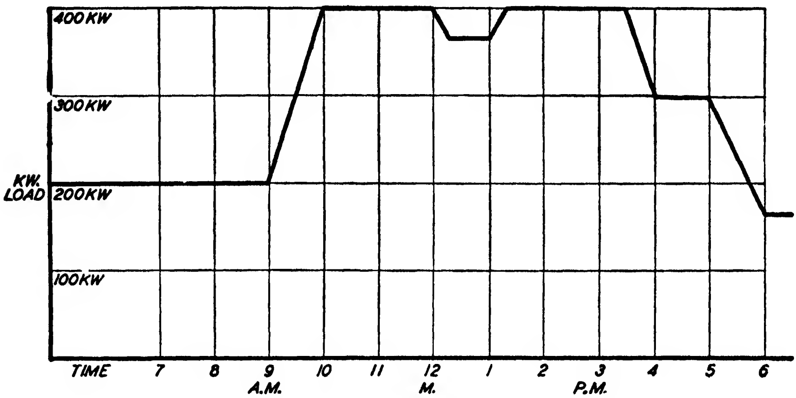


Fig 12 Typical Plant Load

more of the stand-by units will carry the base load when the *base load* machine is out of service.

In Fig. 12, 200 kw is base load and 400 kw is maximum load. The base load generating capacity should consist of one 200-kw machine or two 100-kw machines, with an added 200 kw of capacity, either one or two machines, to take care of peaks. Considering the setup from the standpoint of stand-by capacity, one machine can be taken out of service, leaving 200 or 300 kw of generating capacity, which would allow operation at reduced output during a period of repair or overhauling.

Type of Prime Mover. The selection of the prime mover to drive the generator depends upon several considerations. For example, if suitable boiler capacity is available and exhaust steam is required for heating purposes or for process work in a factory, a reciprocating steam engine or, more probably, a non-condensing steam turbine may be desirable. The exhaust steam may then be utilized. In many instances, process steam at pressures higher than atmospheric pres-

sure are required. Then the modern steam turbine with facilities for extracting or "bleeding" at different pressures is best suited. Fig. 13 shows a 2,500-kw, 60-cycle generator direct-connected to a condensing type turbine.

Comparing these two types of steam-driven prime movers, the advantages of the turbine immediately become evident. Turbines operate most efficiently at higher speeds, 1,800 or 3,600 r.p.m., whereas engines are inherently slow-speed. The combination of a high-speed turbine direct-connected or geared to a high-speed generator and exciter is a less costly and, at the same time, more efficient unit than the slower speed engine with its generator, usually direct-connected, and with a belted or separate exciter set.

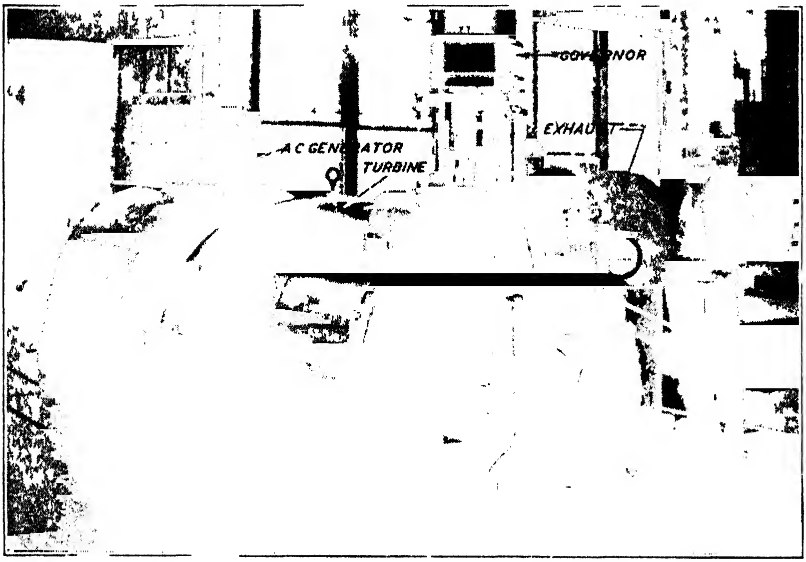


Fig 13 Condensing Steam Turbine Generator Set (2 500 Kw)

During recent years, the internal combustion engine, notably of the Diesel type, has been developed to the point where it can be used efficiently as a prime mover for generators. Diesel engines are available in speeds ranging from 277 r.p.m. in larger sizes to 1,200 r.p.m. in medium and small capacities. Generators are built to direct-connect at any of those speeds. Fig. 14 illustrates typical construction of a generator and exciter for coupling to slow-speed engine.

In some cases, a combination of steam-driven and internal combustion prime movers may be desirable. For instance, during the winter months a turbine-driven generator may be desirable to furnish exhaust steam for heating purposes, with the added requirement of an internal combustion driven unit for peak loads. During the months that require little or no steam, the load may be carried by one or more internal combustion driven generators.

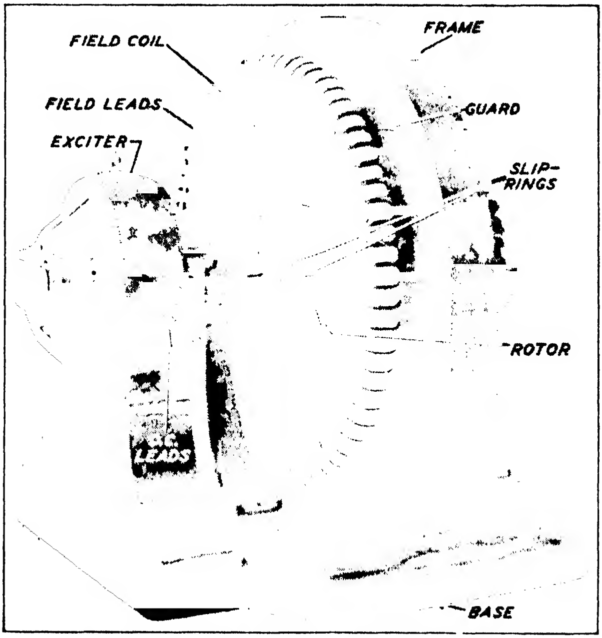


Fig 14 A-C Generator with Direct-Connected Exciter
(250 Kw, 360 R p m)

Mechanical Characteristics of Generators. The nature of enclosures, treatment of windings, and other related characteristics of alternating-current generators are similar to features described for direct-current generators. The same conditions dictate selection of different features regardless of the type of system—direct-current or alternating-current, single or polyphase alternating-current, etc.

SELECTION OF ALTERNATING-CURRENT MOTORS

Alternating-current motors are available in many types for operation on all commercial frequencies, 60-cycle predominating; for

single-phase and polyphase circuits; and in horsepower sizes for different system voltages, as indicated in Table I following:

TABLE I

Standard Motor Voltages and Horsepower

Single-Phase			Two- and Three-Phase		
Voltage	Min. Hp.	Max. Hp.	Voltage	Min. Hp.	Max. Hp.
110-115-120	No min.	1½	110-115-120	No min.	15
220-230-240	No min.	10	220-230-240	No min.	200
440-550	5	10	440-550	No min.	500
....	..	...	2200-2300	40	No max.
....	..	..	4000-4160	75	No max.

GENERAL CONSIDERATIONS

The following factors should be considered when selecting alternating-current motors:

Horsepower Rating. It is, of course, essential to select a motor capable of carrying the required load without overheating and resultant damage to insulation. Modern insulating materials allow a temperature rise on open motors of 40°C. (55°C. for enclosed motors) above an assumed ambient or room temperature of 40°C., or a total temperature of 80°C. on Class A insulated motors. Where ambient temperatures higher than 40°C. are encountered, Class A motors with lower temperature rise, say 30°C., may be used as long as the total temperature does not exceed 90°C. for enclosed motors. These limits may be raised to 110°C. total temperature for open motors and 115°C. for enclosed motors with Class B insulation.

Modern (so-called general-purpose) polyphase motors are not rated up to their maximum safe output, but have a service factor of 1.15 at rated voltage and frequency. For instance, if the load requirement is 22, instead of applying a 25-horsepower motor it is permissible to use a 20-horsepower motor, since 20×1.15 (service factor) $= 23$ horsepower, the permissible load, and is within the accepted safe limits of temperature rise for the insulation. However, the manufacturer's guarantees of efficiency and power factor, which are based on normal rating, do not apply in those instances where the service factor rating is used.

Loads which are fairly constant for long periods require motors rated at the maximum requirement. For example, let us assume that

the steady load for the greater part of the time may be 40 horsepower, but under certain conditions the load may rise to 49 horsepower for periods of 30 minutes or more. A 50-horsepower motor would then be required. This period of permissible short-time overload varies from 15 minutes to 2 hours for different sizes of motors, and such conditions must be referred to the manufacturer.

Special-duty cycles, involving large variations in load, accelerating, and retardation peaks, and periods of standstill require special calculation and should be referred to the manufacturer. A motor of correct thermal capacity and adequate torque to handle all loading conditions of the cycle will be selected. Too large a motor should not be applied—first, because of unnecessary cost, and second, because an underloaded motor produces poor power factor. (See Power-Factor Correction in this section.)

Altitude. Standard ratings of motors are applicable for altitudes not exceeding 3,300 feet above sea level. At higher altitudes, the temperature rise at rated load will increase approximately one per cent for each 330 feet increase in altitude. Special motors are, therefore, required to keep the insulation temperature within allowable limits.

Variation in Voltage and Frequency. The starting torque of all alternating-current motors varies with the square of the voltage impressed on the motor terminals. For instance, consider a motor wound for 220 volts and with rated starting torque equal to 200 per cent of the full-load torque. If the system voltage drops to 206 volts, the actual starting torque will be $\frac{206 \text{ squared}}{220 \text{ squared}} \times 200$ per cent or 175 per cent of full-load torque. Slight changes in frequency will affect only the synchronous speed.

In general, motors will operate successfully (without, however, meeting guarantees) where:

1. The variation in voltage does not exceed 10 per cent above or below normal.
2. The frequency does not vary more than 5 per cent above or below normal.
3. The sum of voltage and frequency variation does not exceed 10 per cent (provided frequency variation does not exceed 5 per cent)

above or below normal voltage and frequency rating as stamped on the motor name plate.

Standardization and Safety. Motors and control must conform to local and national standards in order to (1) be allowed connection to the power circuit, (2) satisfy safety and fire underwriter requirements, and (3) allow lowest possible insurance rates. Recognized standards are as follows:

1. National Electrical Manufacturers Association (NEMA) standards, which specify mounting dimensions for induction motors, allowing ready interchangeability of different makes of motors.
2. American Institute of Electrical Engineers (AIEE) standards, which specify the temperature limits of insulation materials and prescribe methods of rating and testing apparatus.
3. National Electric (NE) code, which is the general guide of city and insurance company inspectors in determining the type of enclosures and protection and installation of motors.
4. State laws, which are directed to increased safety to life and property and reduction of fire hazards.
5. City ordinances, which may include additional required precautions for prevention of human injury or fire damage.

The products of recognized manufacturers incorporate features which satisfy these requirements, and these products may be selected for each application.

TYPES OF ALTERNATING-CURRENT MOTORS

Alternating-current motors may be classified generally as either induction or synchronous types.

Induction Motors. Induction motors, both single-phase and polyphase, are simple in design, sturdy in construction, and require minimum care from the standpoint of operation and maintenance. They can be started by being thrown directly across the line, or by being accelerated automatically with magnetic control devices, without undue precaution as to sequence of operation by the attendant.

Induction motors operate at less than synchronous speed when loaded, the amount of lag or slip varying with the load. The power factor of induction motors is always less than unity and is lagging due to the lagging reactive component of magnetizing current.

All types of induction motors are based upon the principle that a rotating field is set up in the stator which in turn induces currents in the rotor winding. The reaction between the rotor winding and the revolving field causes the rotor to revolve.

Squirrel-Cage Induction Motor. The simplest form of induction motor is the "squirrel-cage" type, so called because its armature or rotating element, with bars short-circuited at their ends by heavy copper end rings, resembles a squirrel cage. See Fig. 15. The squirrel-cage principle is used in both single-phase and polyphase motors. The stator windings are distributed in the same manner as those of an alternator. The line leads are connected directly to the terminals of the stator, and there are no external connections to the short-circuited rotor winding.

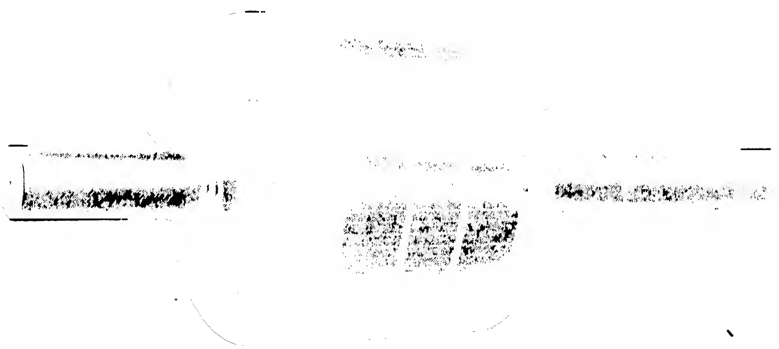


Fig. 15 Showing End Construction of Squirrel-Cage Rotor

Synchronous Motors. Synchronous motors, built commercially only for polyphase circuits, resemble revolving field alternators and, in fact, can be operated as alternators when connected to a driving unit of proper speed. Modern, general-purpose synchronous motors are built to operate under conditions of starting and running torque comparable to those named for induction motors and are about as simple in operation. Their somewhat higher price is not warranted in the smaller sizes, but they are available in horsepower capacities, speeds, and voltages paralleling induction motors above 20 horsepower.

Synchronous motors operate at synchronous speed and at unity power factor, or with leading power factor to compensate for the lagging power factor of inductive devices.

The development of starting equipment, both semimagnetic and magnetic, using automatic field application devices, has made the

synchronous motor practically as easy to operate as the simpler induction motor.

Single-Phase Motors. Because the squirrel-cage, polyphase motor is simpler in mechanical design and superior in operating characteristics to any design of single-phase motor, it is recommended wherever it is possible to obtain economically a three-phase service. However, it is recognized that in many locations, such as in rural and residential sections and in isolated parts of plants and buildings, it is impractical to install a three-phase power circuit for one or a few small motors.

Any Y-connected, three-phase induction motor, when connected with two of its line leads to a single-phase power source, will operate

Fig 16 Squirrel-Cage Rotor for High-Resistance, Split-Phase Motor

as a single-phase induction motor once it is brought up to speed. But such a motor has no starting torque because the course of the moving field produced by the stator winding is, at standstill, more nearly a straight line than a circular one. Therefore, it has no starting torque and will not start unless some means is introduced to cause phase displacement between the fields sufficient to produce an elliptical revolving field. The several principles employed to accomplish this end make the development of the single-phase motor to its present standard of performance an interesting study.

Split-Phase, Single-Phase Motors. The split-phase motor is built with a single-phase stator winding plus an auxiliary winding in space quadrature (90 degrees out of phase) with the main winding. This auxiliary winding is similar to the use of the third phase of a Y-connected three-phase winding where the third phase is 120 degrees out of phase with the main winding. The rotor is of the squirrel-cage type.

In the early motors of this type, the supply current was divided before it reached the motor. One branch passed through a reactance to the main winding, and the other passed through a noninductive resistance to the auxiliary or starting winding. When current was applied to this connection, the motor came up to speed after which the starting winding and the line reactance were cut out of the circuit by an external manually operated starting box.

In modern practice, the split-phase motor is built only in small sizes up to ¼ horsepower, for applications whose torque and duty

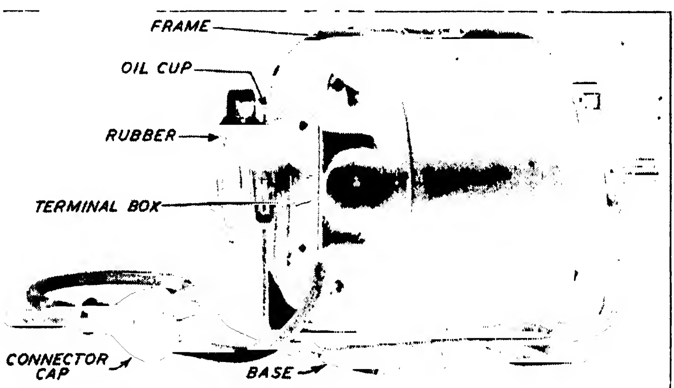


Fig 17 Split-Phase Motor with Rubber Cushion Base

requirements are not severe. In these motors, the reactance is omitted; the extra resistance is produced in the starting winding itself by the use of high-resistance wire. The starting winding is cut out of the circuit by a centrifugally operated switch when the motor has come up to speed. See Figs. 16 and 17. Required control equipment is very simple and need be no more than a one- or two-pole switch to disconnect the two line terminals from the power source.

Split-phase motors are essentially constant speed. For very special low-torque applications, such as variable speed propeller fans, the variable speed is secured by inserting steps of resistance in series with the line. This practice is not recommended without special care in application, because operation below the speed at which the centrifugal switch is actuated will burn out the starting winding.

Repulsion-Induction Single-Phase Motors. The repulsion-induc-

tion motor is a self-contained unit capable of starting heavy loads and maintaining reasonably constant speed under varying load conditions.

The characteristics of the direct-current series-wound motor are well known. Operating through a wide range of speed and torque, this type has, however, no inherent speed regulation and its use is consequently confined either to fixed loads, like fans or pressure blowers, or to varying loads where the motor-controlling device is constantly under the operator's guidance. The speed, torque, and load characteristics of the series-commutator-type alternating-current motor being distinctly analogous to that of its direct-current prototype, the design fails to meet the requirements of constant-speed power service, this service demanding a motor which maintains good regulation after having once been brought up to speed, with torque values increasing as speed decreases; in other words, characteristics approaching those of the direct-current compound motor having the usual proportion of series-field winding.

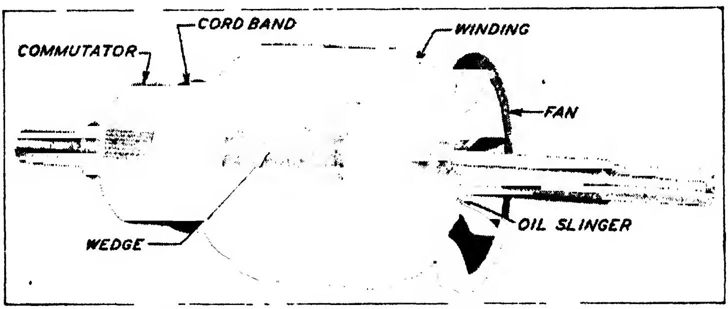


Fig. 18. Rotor for 3 Hp , 1,800 R p.m. Repulsion-Induction Motor

The repulsion-induction motor, however, gives this combination of series and shunt characteristics; that is, a limited speed and an increased torque with decrease in speed. In the straight repulsion motor, to secure the necessary starting torque, a direct-current armature is placed in a magnetic field excited by an alternating current and short-circuited through brushes set with a predetermined angular relation to the stator. To further improve the operating characteristics of the plain repulsion motor, a second set of brushes (i.e., the compensating brushes) is placed at 90 electrical degrees from the main short-circuiting brushes (i.e., the energy brushes). The compensating field is auxiliary to the main field and impresses upon the

armature an electromotive force in angular and time phase with the electromotive force generated by the main field. In addition to correcting phase relation between the current and the voltage, thus giving approximately unity power factor at full load and power factors closely approaching unity over a wide range of load, the compensating field serves to restrict the maximum no-load speed and also permits, where varying speed service is involved, slight increase

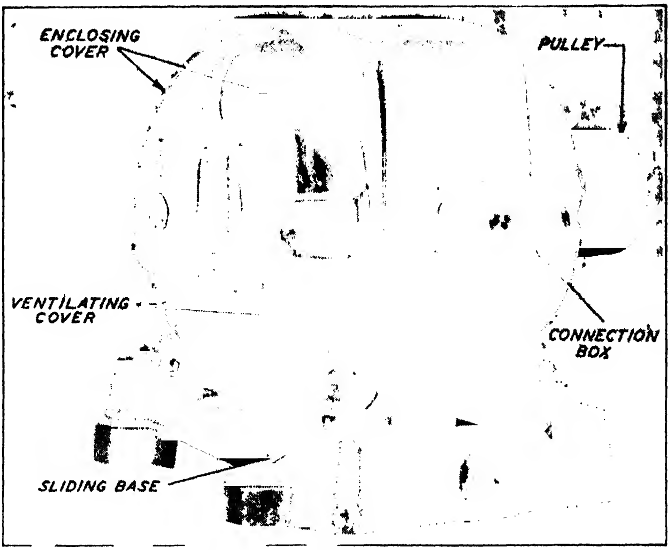


Fig 19 Repulsion-Induction Motor (1 Hp) with Sliding Base

over synchronous values. The compensated repulsion motor is practically an induction motor capable of operation either above or below synchronous speed, possessing high starting torque and high power factor at all loads as well as excellent efficiency constants. The motor has no tendency to spark or flash over, since the armature coils, successively short-circuited by the energy brushes, are not inductively placed in the magnetic field and consequently have only to commutate a low generated voltage. See Figs. 18 and 19.

Repulsion-induction motors may be started by throwing directly across the line. Starting rheostats are available for use where it is desired to reduce starting current to minimum.

These motors are sold in several types: constant-speed; constant-speed reversible; brush-shifting, adjustable varying speed (with series

characteristics), and adjustable varying speed, reversible. The adjustable varying speed types are applicable to the same type of loads as series direct-current motors. They provide 3:1 range of speed adjustment by the simple expedient of shifting brushes.

Capacitor Type Single-Phase Motors. The capacitor motor, employing a capacitor (static condenser) in the auxiliary winding

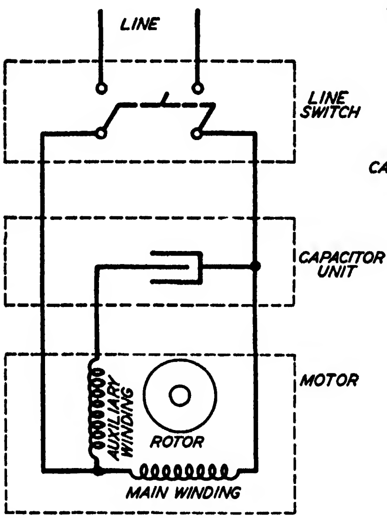


Fig 20 Connection Diagram for Low-Torque Capacitor-Fan-Motor

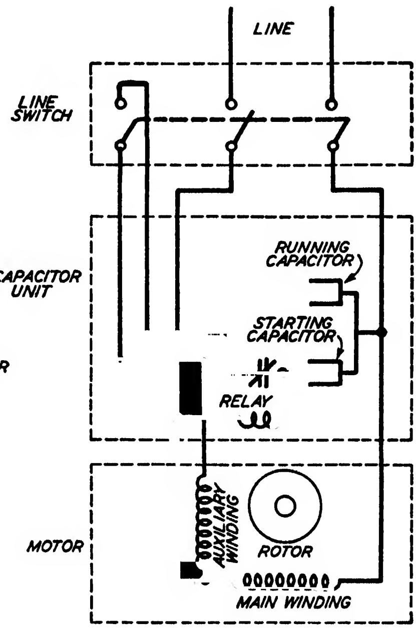


Fig 21 Connection Diagram for High-Torque Capacitor Motor

circuit, is a recent development which is proving to be very popular. The principle of operation is identical to that of the split-phase motor, except that capacitance and inherent resistance instead of reactance and resistance are combined to produce the out-of-phase component of current with consequent starting torque.

The stator is wound with a main winding and an auxiliary winding spaced 90 electrical degrees out of phase. The rotor is of the squirrel-cage type, with the bars and end connections usually of aluminum, cast integrally.

Capacitor motors are of two types: low-torque, for fan duty, and high-torque for general-purpose applications. Fig. 20 shows the

connections of a low-torque motor with the capacitor permanently in the circuit—hence the term, capacitor start and run. In some motors the capacitor is in circuit only during starting. Such motors are

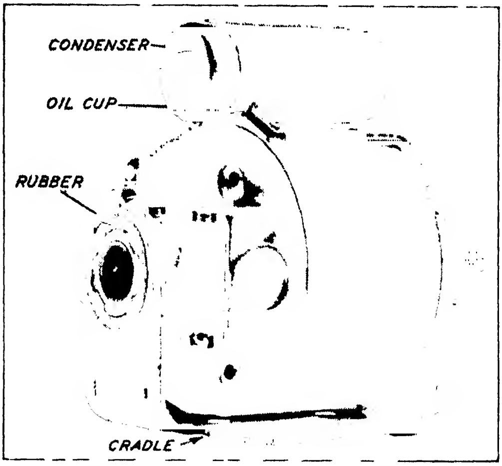


Fig 22 Small Capacitor Start Induction Motor with Motor-Mounted Capacitor and Resilient Base

termed capacitor-start induction-run. In all sizes, the capacitor is mounted externally—on top of the motor in sizes up to approximately ½ horsepower, and separately, on wall or floor, in sizes up to 10.

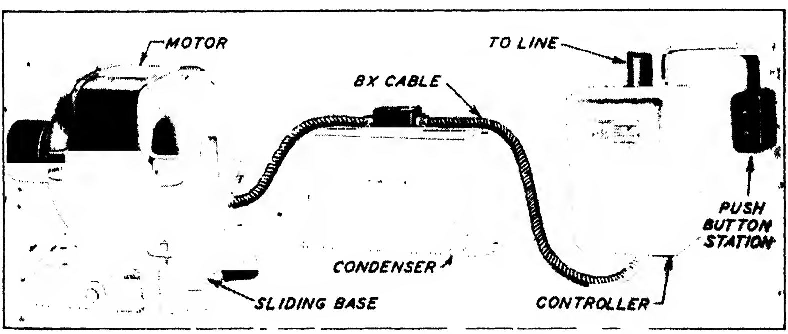


Fig. 23 High-Torque Capacitor Motor (5 Hp) with Separately Mounted Capacitor Unit and Control

High-torque capacitor motors employ two condensers, one continuously rated for running, and the other intermittently rated for starting. A relay, mounted in the capacitor box, disconnects the starting condenser automatically when the motor has accelerated.

Fig. 21 shows connection of the high-torque type, and illustrates the need of a three-pole switch. Capacitor motors possess all the desirable characteristics of high power factor, high efficiency, permissible starting current for across-the-line starting, and quiet operation because of absence of centrifugal devices and commutator.

Figs. 22 and 23 illustrate two types of capacitor motors.

High- and low-torque fan motors may be furnished with adjustable varying speed control, allowing speed reduction of approximately 35 per cent. Such control is not applicable to high-torque, general-purpose motors, but the recent development of two-winding, multi-speed capacitor motors opens up that field to this type of motor.

POLYPHASE INDUCTION MOTORS

All types of polyphase motors described here are available for two-phase as well as three-phase circuits, with the exception of the two-speed, reconnected-winding type.

SQUIRREL-CAGE TYPES

The squirrel-cage induction motor is the simplest type of motor available and greatly outnumbers all other types in use. Fig. 24 is typical.

Constant-Speed Squirrel-Cage Motors. The constant-speed motor with single stator winding can be altered as to operating characteristics by changing the design of the rotor. In this manner, torque and starting current characteristics are produced to meet various operating conditions imposed by different loads and power company limitations. These characteristics are summarized as follows:

A. Normal torque, normal starting current—for general application, and generally requiring reduced-voltage starting equipment above 5 horsepower. Has low slip for close speed regulation.

B. Normal torque, low starting current—for general application; designed to meet most power company requirements as to starting current for motors up to and including 30 horsepower, to be thrown across the line. Has low slip for close speed regulation.

C. High torque, low starting current—designed to accelerate heavy starting loads at infrequent intervals. High-resistance rotor required to produce torque characteristic also produces the desirable low starting current. Has low slip for close speed regulation.

D. High torque, high slip—designed to accelerate heavy loads without shock. This type of motor is especially desirable for use with flywheels, because its

high-slip characteristic allows variation in speed without objectionable current pulsations to line and without undue heating of motor, if load peaks occur less than 25 times per minute.

All of the above types of motors have relatively high efficiency and power factor, although the high-slip motor sacrifices some efficiency. Table II, following, indicates average values for motors of the types described above, in ratings 7½ to 20 horsepower, 1,800 r.p.m., 60 cycles:

TABLE II

Efficiency and Power Factor for Squirrel-Cage Induction Motors

Type of Motor	Starting Torque	Maximum Torque	Per Cent Slip	Starting Current Across-the-Line*	Efficiency*	Power Factor*
A	190	250	3	650	85	89
B	190	220	3	500	86	86
C	240	240	3 5	500	84	84
D	275	280	9	550	82	88

*Per cent of full load.

Values of starting and maximum torque are in percentage of full-load synchronous torque (T), derived from the following formulas:

$$T = \frac{hp. \times 5250}{r.p.m.} \tag{2}$$

where T = torque in pounds at one-foot radius
$hp.$ = horsepower rating of motor
$r.p.m.$ = synchronous speed in revolutions per minute

$$\textit{Slip in per cent (at full load)} = \frac{\textit{Syn. speed} - \textit{full-load speed}}{\textit{Synchronous speed}} \tag{3}$$

$$\textit{Full-load current} = \frac{\textit{Horsepower} \times 746}{\textit{Line voltage} \times \sqrt{3} \times \textit{Efficiency} \times \textit{Power Factor}} \tag{4}$$

Efficiency and power factor at full load, expressed as decimals.

Multispeed Squirrel-Cage Motors. Multispeed motors are a modification of constant-speed, single-winding motors, with squirrel-cage rotors, and are of the following types:

1. Reconnectible-winding, two-speed motors, in which a single stator winding is reconnected in two different polar groupings, one connection always having one-half the number of poles of its complement. For instance, 4/8 poles to give 1,800/900 r.p.m., 6/12 poles to give 1,200/600 r.p.m., or 8/16 poles to give 900/450 r.p.m.—all at 60 cycles. Reconnectible-winding motors are available with two speeds for variable-torque, constant-torque, and constant-horsepower

applications. This type of motor is not available for operation on two-phase systems because of the difficulty of regrouping the coils of a two-phase winding to obtain different polar connections.

2. Two-winding, two-speed motors are built with two separate stator windings in the same slots and are, therefore, essentially two separate motors in the same frame, using the same squirrel-cage rotor. This type is adaptable to two-phase as well as three-phase circuits and is available for variable-torque, constant-torque, and constant-horsepower applications. The two speeds need not be limited to ratios of two to one, as for reconnectible motors, but are necessarily

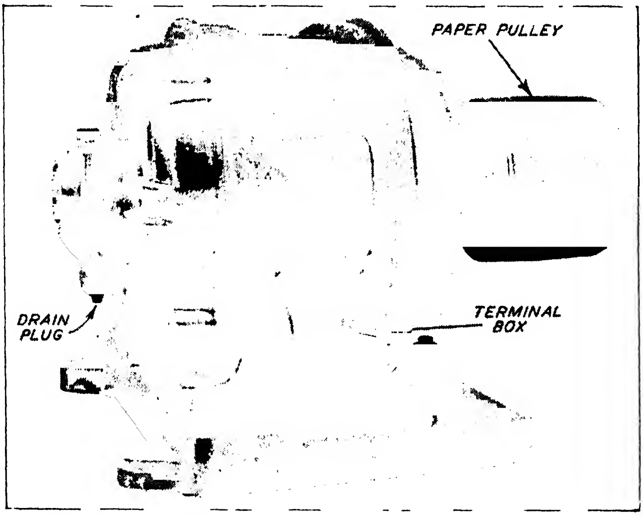


Fig. 24. Low-Voltage, Polyphase, Squirrel-Cage Induction Motor with Sliding Base (20 Hp, 1,200 R p.m)

limited in range for constant-torque and constant-horsepower types because of limitation of output in each frame size. Variable-torque designs allow wide selection of speeds in the range 1,800/1,200/900/720/600/450 r.p.m. with 1,800, 1,200, 900, and 720 r.p.m. being the top speeds for any combination of speeds.

3. Three- and four-speed two-winding motors. A further combination of two separate windings, each of which is reconnectible in polar groupings, allows the derivation of three or four speeds from one motor. This type is limited to three-phase circuits for the reason given in paragraph 1 above. For example, one winding reconnectible from 4 to 8 poles, and another from 6 to 12 poles gives a motor rated 4/6/8/12 poles or 1,800/1,200/900/600 r.p.m. at 60 cycles. Another combination available is 6/8/12/16 poles giving 1,200/900/600/450 r.p.m., also at 60 cycles. A combination such as 1,200/900/720/600 r.p.m. would require a special three-winding motor. Three- and four-speed motors are also available with variable-torque, constant-torque, or constant-horsepower characteristics.

Multispeed motors were developed for applications requiring operation at one or more definite speeds below top speed, at relatively

high efficiency and at comparatively low first cost. They meet these requirements wherever adjustable-varying speed with a larger number of control points is not required.

Multispeed motors are designed with several starting-current and torque characteristics. Controlling devices for these motors are necessarily more costly than for single-speed motors, but are relatively simple.

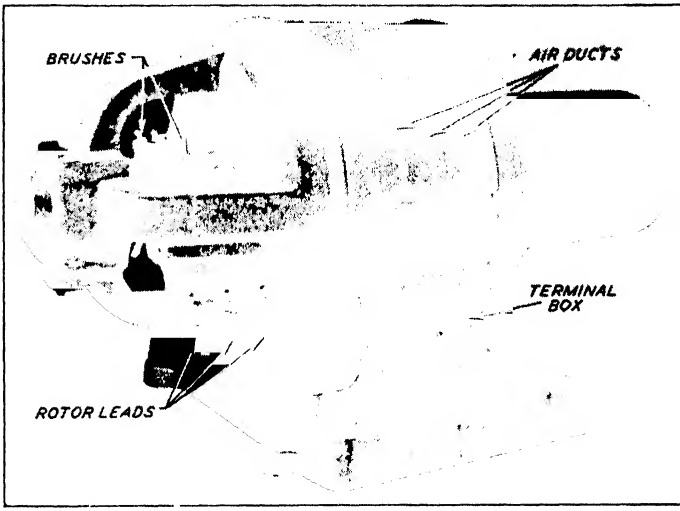


Fig. 25. Open Type Wound-Rotor Induction Motor (40 Hp., 900 R.p.m.)

WOUND-ROTOR TYPE

In the wound-rotor type of induction motor, the stator (or primary) is wound exactly as in the squirrel-cage type, but the rotor (or secondary) is polar-wound, with the ends of the Y-connected rotor windings brought out to three collector rings mounted upon and insulated from the shaft. Thus, this type is frequently called a "slip-ring" motor. See Fig. 25. Brushes mounted in stationary brush holders complete the circuit to an externally mounted Y-connected secondary resistance.

The wound rotor, with external connections to slip-rings, allows the use of several layouts of external resistance to produce the desired torque during starting, or at reduced speed on speed-regulating points. This type of motor is applicable on loads requiring heavy

accelerating effort, and in locations where the starting current must be kept at a low value. The slip-ring motor offers the highest possible starting torque per ampere, full-load current producing approximately full-load torque at starting.

Control for simple starting duty is furnished with intermittent-rated starting duty resistor of such resistance value that approximately 250 per cent starting torque is produced with only 300 per cent starting current. Both values may be reduced, where required, by changing the resistance.

Slip-ring motor control for adjustable varying speed is designed with a continuous-duty resistor which allows the motor to be run continuously on any of its reduced speed points with a part of its resistor in series with the rotor windings. The secondary resistance layout, adjustable for varying speed control, must be differently designed for different types of load, such as variable torque—fan duty, and constant torque—machine duty. Therefore, these details must be furnished to the manufacturer.

Accurate speed control cannot be obtained below 50 per cent speed reduction, that is, two-to-one speed range, because of the proportions of secondary and external resistance values. Beyond that range, the speed change due to slight change of load torque becomes disproportionate.

Although the slip-ring motor with proper accessories allows varying speed control at relatively low first cost, its operation at reduced speeds is at the expense of efficiency. The electrical energy dissipated in the external secondary resistance must be added to the normal motor losses in determining overall efficiency. Operation at 50 per cent speed on a constant-torque load will be at approximately 50 per cent overall efficiency. For this reason, it is desirable to select, if possible, definite speeds at which the drive may operate, and use a suitable multispeed motor. If adjustable varying speed over a wide range is required, and if the motor must operate at reduced speeds a large part of the time, the brush-shifting motor may be the most economical, even at a higher first cost.

Brush-shifting Adjustable-Speed Motors. The brush-shifting adjustable-speed motor is a self-contained, reliable driving unit for operation on polyphase alternating-current circuits. These motors are built in sizes from 2 to 50 horsepower for three-to-one and four-to-

one speed range for constant-torque applications, and have shunt characteristics under these conditions. Motor speed is controlled by shifting the brushes, thus providing an infinite number of speed points within the speed range. Fig. 26 shows the connections of this type of motor.

The stator has one winding (the secondary), which is constructed like the stator (primary) winding of an induction motor, except that phases are electrically independent and both ends of each phase are

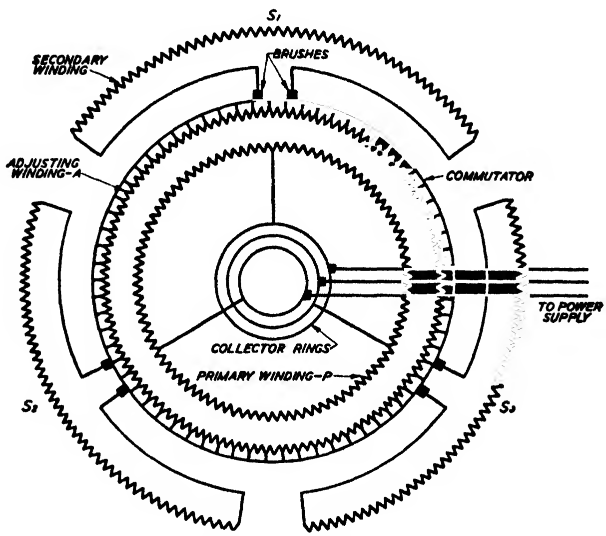


Fig. 26 Connections of Brush-shifting Adjustable-Speed Motor

brought out for connection to the commutator brushes. The rotor is provided with two windings placed in the same slots. The inner winding (primary) is identical in construction with the stator (primary) winding of a normal induction motor and is connected to the collector rings, to which the power is applied. The outer, or adjusting, winding is connected to the commutator in the same manner as in a direct-current motor.

Thus, the brush-shifting motor may be compared with the wound-rotor induction motor, having its primary winding in the rotor and its secondary on the stator. In addition, this machine has an adjusting winding in the rotor similar to a direct-current armature winding and connected to a commutator. The motor is provided

with two brush-holder yokes arranged to shift in such a way as to vary the voltage on the secondary winding.

One end of each phase of the stator (secondary) winding is connected to brushes on one brush yoke and the opposite end of each phase is connected to brushes on the other yoke. When the brushes, to which each end of a secondary phase is connected, are on corresponding commutator segments, the adjusting winding is, in effect, idle, the secondary winding is short-circuited, and the motor runs as an induction motor, with speed corresponding to the number of poles and frequency of supply. As the brushes are moved apart, a section of the adjusting winding is included in series with the secondary winding, causing the secondary winding to generate a voltage impressed upon it by the adjusting winding, thereby causing the motor to change its speed. Moving the brushes in one direction raises the speed, and moving them in the other direction reduces the speed. The motor operates both above and below the synchronous speed.

The motor is started on full voltage with the brushes in the low-speed position, as standard procedure. In this position, starting current is 125 per cent to 175 per cent of the full-load current at maximum speed. In most ratings, motors develop 200 per cent starting torque with less than 175 per cent starting current; in the larger sizes, starting torque is approximately 160 per cent, with less than 160 per cent starting current.

Where operating conditions require, it is possible to start the motor with the brushes in any position. In such cases, proper secondary resistance should be supplied to limit excessive current at starting. With such resistance, starting torque at the higher speed brush positions will be at least 250 per cent of normal full-load torque.

In the low-speed brush position, maximum running torque varies from 200 per cent of normal full-load torque on the smallest size to 160 per cent on the largest size. In the high-speed position, the maximum torque is at least 250 per cent of normal full-load torque on all sizes.

The efficiency of brush-shifting motors remains nearly constant over the greater part of their speed range, but it is somewhat lower at low speed. The average efficiency is high as compared with that of wound-rotor induction motors with secondary resistance, or as compared with direct-current motors and the apparatus necessary to convert alternating current to direct current.

Power factor is high when the motor is running at high speed, and even at synchronous speed the power factor is approximately the same as that of an induction motor of similar rating.

With full-load speed, approximately 1650/550 r.p.m. for a three-to-one ratio motor, the no-load speeds will be as follows: with the brushes in the maximum-speed position, 5 to 11 per cent higher than the rated full-load speed; with the brushes in the minimum-speed position, 17 to 43 per cent higher than the rated minimum speed.

These motors will operate continuously in either direction, provided the brush mechanism is set for the desired rotation. They may

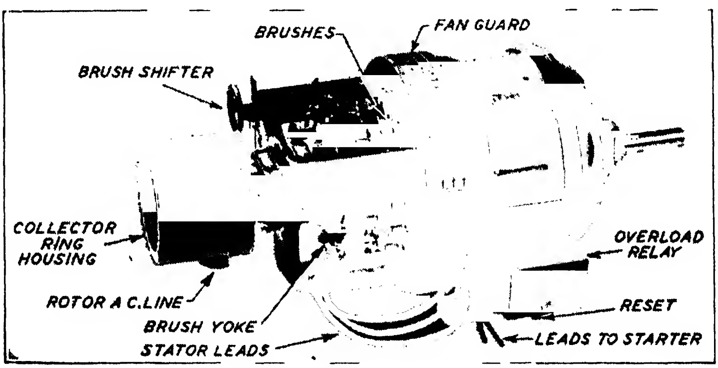


Fig 27 Brush-Shifting Adjustable-Speed Motor

be reversed by interchanging two line leads, as on an induction motor. Reverse operation should be allowed for short periods of time only, as the motor characteristics are impaired unless the brush-shifting mechanism is reset according to the instructions furnished with each motor.

Any creeping speed down to 50 per cent of the minimum rated speed may be obtained at rated torque for half-hour operation by means of secondary control. Overload or stalling protection is not provided when the motor is operated under these conditions.

Brush-shifting motors should be connected to the source of power in the same manner as any three-phase induction motor—by connecting the motor to the three lines. A magnetic switch, operated by a push-button station in conjunction with a temperature overload relay, mounted on the stator frame and connected in the stator circuit, provides low-voltage and overload protection at all operating

speeds. Slow-down or creeping speeds may be obtained by adding resistance in series with the secondary circuit and providing a switch for short-circuiting this resistance for normal operation.

Changes in speed by brush shifting are obtained in one of the three following ways:

1. Shifting the brushes by means of a handwheel or handle mounted on the motor. Fig. 27 shows a typical motor with motor-mounted handwheel.

2. Shifting the brushes by means of a handwheel or handle on a remote brush-shifting mechanism, which is mounted at a location convenient to the operator and connected to the motor by a chain.

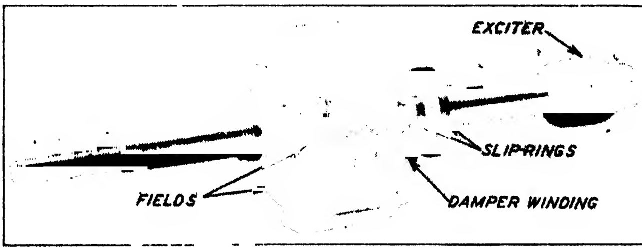


Fig 28 Rotor for 75 Hp 1 200 R p m Synchronous Motor with Direct-Connected Exciter

3. Shifting the brushes by means of a pilot motor and reduction-gear mechanism, which is mounted on the motor and controlled by push buttons located elsewhere.

Miscellaneous Polyphase Motors and Variable-Speed Systems. For description of the Noel Capacitor motor and Fynn-Weichsel variable-speed motors, see Power-Factor Correction.

Heavy-duty adjustable varying speed drives are available in the Krämer and Scherbius systems of speed control. Both employ a slip-ring motor as the main driving unit and use accessory equipment to derive changing excitation and power for range of speed required. Additional details concerning these systems may be obtained from manufacturers of electric equipment.

SYNCHRONOUS MOTORS

Synchronous motors, as the name implies, operate at synchronous speed—that is, with no slip. They are practically identical in construction with (synchronous) alternators or generators, having a

three-phase wound stator and a rotating field consisting of direct-current excited coils of alternately opposite polarity, connected in series to a direct-current excitation source at its slip rings. Modern practice is to use 125-volt direct-connected exciters for each motor unit, particularly at the higher speeds. At low speeds, it is sometimes economical to supply excitation, either 125 or 250 volt, to one or more motors from a high-speed motor-driven exciter set. (Generally with additional stand-by set.) To provide uniform and sufficient starting

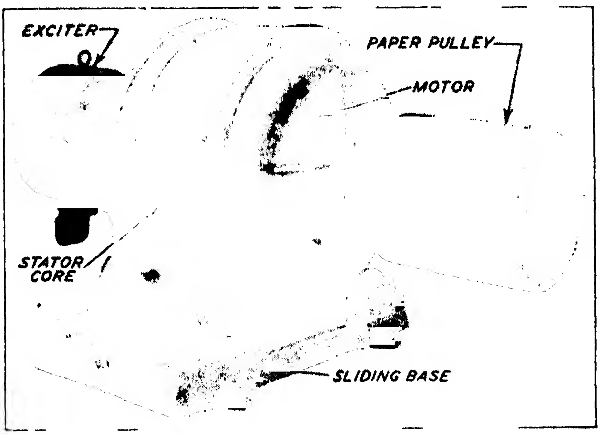


Fig 29 Synchronous Motor and Base for Pulley Drive (50 Hp, 80 Per Cent Power Factor, 1,200 R p m)

torque for general use, synchronous motor rotors are built with starting windings imbedded into the faces of the field pole pieces and short-circuited at their ends by circular rings. These are similar to the squirrel-cage winding of an induction motor. See Fig. 28.

Synchronous motors operate with minimum excitation at unity power factor—that is, when the line current drawn by the motor is exactly in phase with the voltage. Unity power-factor motors are widely used to raise the average power factor of a plant employing a large number of smaller induction-type motors operating at lagging power factor, that is, with line current lagging behind voltage by an angle whose cosine equals the power factor expressed as a decimal.

When increased excitation is applied to the field of a synchronous motor, we have what is known as a leading power-factor motor capable of supplying leading reactive kva to a system to compensate for

lagging reactive kva drawn by induction machines. Such motors are generally rated in horsepower at .80 leading power factor. The power factor corrective feature of synchronous motors will be discussed in more detail under Power-Factor Correction.

Unity power factor and .80 power factor general-purpose synchronous motors are available in all ratings from 20 horsepower up. Designed with starting torque and pull-in torque of approximately 110 per cent of rated full-load torque, they can be applied to all normal duties except those requiring heavy starting torque and extremely high maximum or pull-out torque. See Figs. 29 and 30.

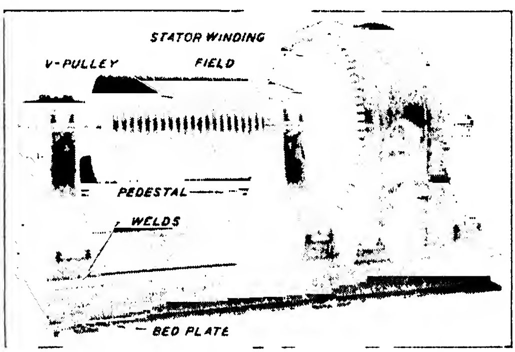


Fig 30 Three-Phase, 60-Cycle Synchronous Motor with Outboard Bearing and Sheave for V-Belt Drive (300 Hp, 80 Per Cent Power Factor, 600 R p m, 2,200-Volt)

Synchronous motors are best suited for loads requiring a nearly constant torque—that is, one without instantaneous pulsations. On a load producing pulsations in shaft torque, a synchronous motor will draw high current from the line at each pulsation because, being a synchronous machine, it will tend to pull out of step. Wherever synchronous motors are used to drive reciprocating compressors and similar machines, flywheel effect to absorb the pulsations must be provided in the rotor of either or both the motor and the compressor.

In general, since the major utility of synchronous motors is derived from their unity power-factor operation or their ability to supply leading reactive kva, their relatively higher cost (as compared with induction motors) cannot be justified except on practically continuously operated machines. Obviously, no power-factor correction can come from such a machine when it is not operating.

Synchronous motors can be started by throwing directly across the line, and, when so started, the current drawn by a high-speed motor is approximately that of a normal-torque, normal-starting-current motor—that is, 600 per cent. When started by reduced-voltage starting equipment, the starting current corresponding to full-load torque is from 350 to 400 per cent of full-load current. Low-speed motors seldom require reduced-voltage starting equipment because their average full-voltage starting current is only 300 per cent of full-load current.

Starting equipment for synchronous motors is available in semi-magnetic and full-magnetic forms, both for full-voltage and reduced-voltage starting. In all forms, the field is applied automatically. This feature eliminates much of the necessity for care previously required in the operation of synchronous motors.

ERECTING AND LINING UP ALTERNATING-CURRENT GENERATORS

The erecting and lining up of alternating-current generators and motors involve the same principles and procedures as for direct-current machines. The same general details regarding making of electrical connections of direct-current machines also apply for alternating-current machines.

Wiring Connections. Wiring connections for an alternating-current generator consist, essentially, of leads between generator stator terminals and line side of generator switch, and leads from load side of generator switch to bus. The excitation circuit is connected from source through field switch to generator field and includes a rheostat in series with the field circuit. See Fig. 31.

If the excitation source is a direct-connected exciter, the field rheostat may operate only on the exciter shunt field; or, on larger machines, there will be both an exciter field and a generator field rheostat operated by a concentric type switchboard mechanism. There will also be accessory voltmeters, frequency meter, ammeters, etc., depending on the refinements required in the controlling switchboard. For small generators under 100 kva and not to be operated in parallel with other units, the field switch is often omitted since there will be no occasion to "kill" the field.

Practically all generators, whether for single or for parallel operation, require generator-voltage regulators. These regulators act upon the exciter field to maintain constant generator terminal voltage. The voltage regulation of a standard alternating-current generator is approximately 30 per cent—that is, the voltage at constant excitation will drop 30 per cent from no load to full load. It is impractical to adjust the excitation manually for varying load.

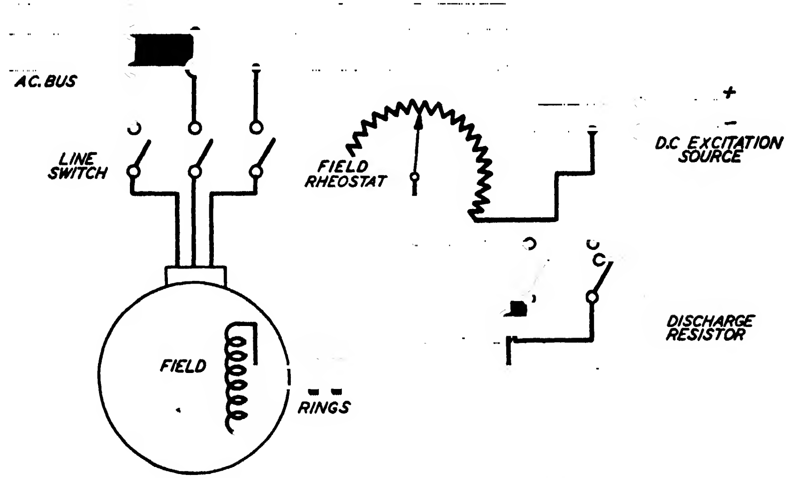


Fig 31 Typical A-C Generator Wiring Diagram

Parallel Operation. Generators which are to be operated in parallel demand voltage regulators. To assure the maintenance of system stability, the combination of generator-voltage regulator and exciter characteristic should be as nearly identical as possible. Furthermore, the speed regulation characteristic of speed governing devices on prime movers must be carefully paralleled.

To run two alternators in parallel, several conditions have to be fulfilled: The incoming machine—as in the case of direct-current machines—must be brought up to nearly the same voltage as the first one; it must operate at exactly the same frequency; and, at the moment of switching in parallel, it must be in phase with the first machine. This correspondence of frequency and phase is called "synchronism."

Synchronizing Alternators by Lamp Indicator. It is impossible with mechanical speed-measuring instruments to determine the

speed as accurately as is necessary for this purpose. There is, however, a very simple method of electrically determining small differences in speed or frequency. In Fig. 32, let M and N represent two single-phase alternators, which can be connected by means of the single-pole switch $A—B$. Across the terminals of the switch is connected an incandescent lamp L, capable of standing twice the voltage of either machine. When $A—B$ is open, the circuit between the machines is completed through L. The two machines may be connected in parallel as follows: Assume machine M already in operation; bring up machine N to approximately the proper speed and voltage; then watch lamp L. If machine N is running a very little slower or faster

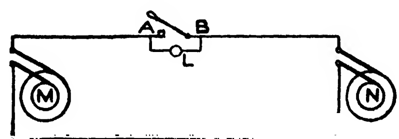


Fig. 32. Diagram of Two Single-Phase Alternators Arranged in Parallel

than machine M, the lamp L will glow for one moment and be dark the next. At the instant when the voltages are equal in pressure and phase, L will remain dark; but when the phases are displaced by half a period, the lamp will glow at its maximum brilliancy. Since the flickering of the lamp is dependent upon the difference in frequency, the machines should not be thrown in parallel while this flickering exists. The prime mover of the incoming machine must be brought to the proper speed; and the nearer machine N approaches synchronism, the slower the flickering. When it is very slow, and at the instant when the lamp is dark, throw the machine in parallel by closing the switch across $A—B$. The machines are then in phase, and tend to remain so, since if one slows down, the other will drive it as a motor. It is better to close the switch when the machines are approaching synchronism rather than when they are receding from it; that is, at the instant the lamp becomes dark.

Fig. 33 shows the method of synchronizing high-voltage alternators through step-down transformers. The first machine to be started becomes "bus" and succeeding machines are paralleled, "machine to bus." When two three-phase alternators are first placed

in operation, synchronizing connections should be made across each phase. If all the lamps become bright or dark simultaneously, the alternators are ready for parallel operation. After all phases have once been tested, it is only necessary to compare a corresponding phase from each machine to indicate synchronism.

The connections, as shown in Fig. 33, indicate synchronism when the lamps are dark. If it is desired that a condition of synchronism

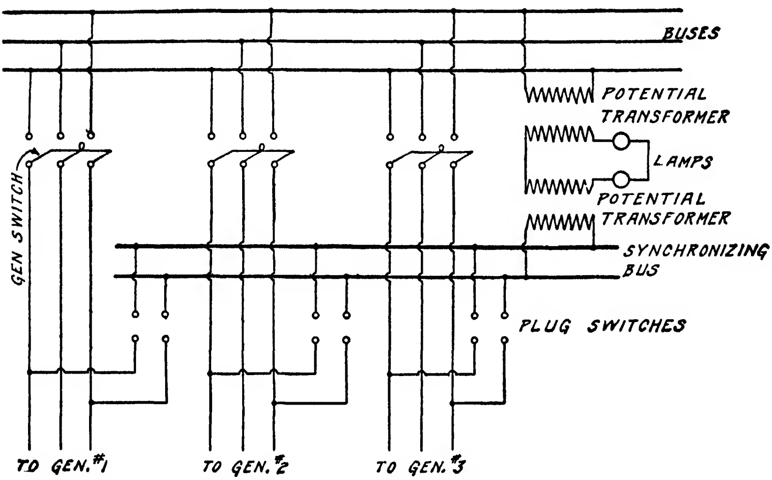


Fig. 33 Diagram of Connections for Synchronizing High-Voltage Alternators through Step-Down Transformers

shall be indicated when the lights are at maximum brightness, reverse the secondary connection of either one of the potential transformers.

Synchronizing Alternators by Means of a Synchroscope. The synchroscope affords the quickest and safest means for paralleling machines, since it shows when the machines are in step and in phase, indicating by the position of the needle the difference in the phase relations between the machines, and telling whether the incoming machine is running too fast or too slow. It is superior to synchronizing with lamps, because the latter give no indication of the relative speed of the incoming machine. The lamps will indicate when the machines are of the same frequency, but the phase relations can be judged only by the brilliancy of the light.

When synchronizing with lamps dark, the phase relations of the machines will be shown by the brilliancy of the light to a point where

the machines are approximately 45 degrees out of phase, below which point there will not be sufficient voltage across the lamp to make it glow. Again, in case there is an inopportune failure of the lamp, the operator might be misled and throw the machines together when out of phase, with possible disastrous results.

When synchronizing with lamps bright, it is difficult to determine, after watching the lamps for some time, at just what instant

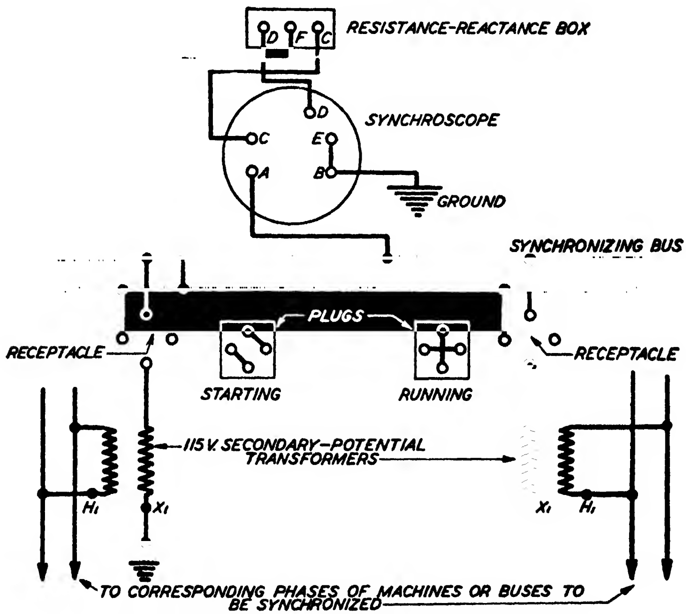


Fig 34. Synchronizing by Use of Plugs and Synchroscope

they are burning at full brilliancy, and therefore, at just what instant the machines are in synchronism.

Fig. 34 shows a method of connecting a synchroscope to two machines (one running and one starting) by means of plugs and receptacles mounted on the switchboard. Either machine may be the "Starting" or "Running" unit. To insure safe operation, only one of each of the plugs marked "Starting" and "Running" should be available at any switchboard. H_1 and X_1 are polarity markings on the potential transformers.

Fig. 35 shows connections for using a synchroscope and synchronizing switches to accomplish the same method of synchronizing,

as shown in Fig. 34, with the added safeguard of oil circuit breaker interlocks, a feature which allows the closing of only the breaker of the machine being synchronized. As in the plug method, one each of "I" and "R" removable handles are furnished for each switchboard.

When two alternating-current generators have been connected in parallel, the division of load should be adjusted. This cannot be

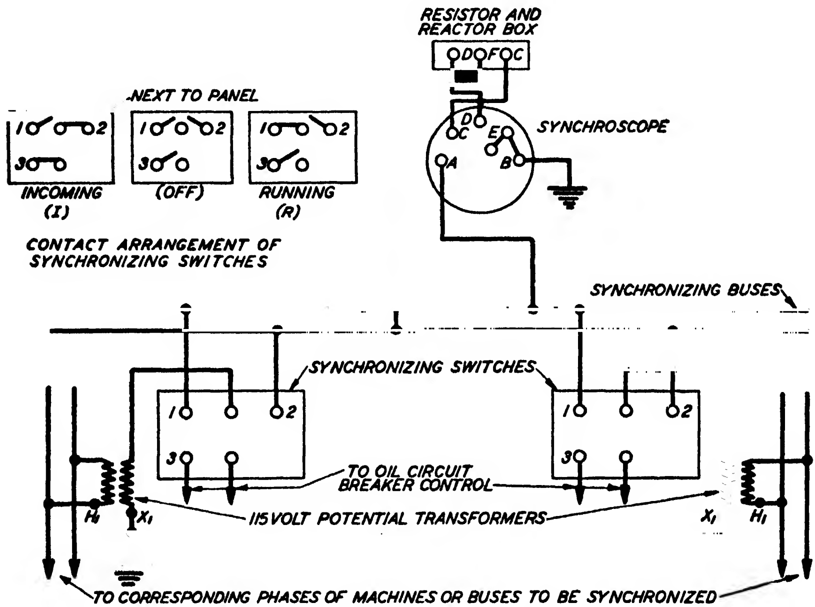


Fig. 35 Synchronizing with Synchroscope and Synchronizing Switches Removable Handle *I* Effects Contact Arrangement "Incoming", Removable Handle *R* Produces "Running"

accomplished as in direct-current machines by adjustment of the field rheostat. Change in field strength will cause more current to flow, but it will be 90 degrees out of phase with the voltage and will not represent actual power. The only way to make the two machines supply proportional amounts of power is to adjust the speed of their respective prime movers. The governors of engines driving alternators, operating in parallel, should be provided with a means whereby the speed can be adjusted within a small range without throttling and while running. Without this refinement, trouble will be encountered when trying to synchronize and adjust for proper division of load. If it is desired to make the machine carry more load, its prime

mover must be adjusted for an increase in speed, and conversely to make the machine carry less load.

If it is found necessary to increase the voltage of machines operating in parallel, the rheostats of all machines should be adjusted proportionally. If the rheostat of only one machine is shifted, cross currents will be caused to flow between the paralleled machines. These cross currents do not represent actual power but do cause undesirable heating of the machines.

OPERATION

Directions for Running Generators and Motors. *Preliminary Run with No Load.* If possible, a new machine should be run with no load or with a light one for several hours. It is bad practice to start a new machine with its full load or even a large fraction of it. This is true even if the machine has been fully tested by its manufacturer and is apparently in perfect condition, because there may be some fault produced in setting it up, or some other circumstance that would cause trouble.

All machinery requires some adjustment and care for a certain time to get it into smooth working order.

Voltage and Current Regulation. A generator requires that its voltage or current should be observed and regulated if it varies. The attendant should always be ready and sure to detect and overcome any trouble, such as sparking, heating, noise, abnormally high or low speed, etc., before any injury is caused. Such directions should be thoroughly committed to memory in order promptly to detect and remedy any trouble when it occurs suddenly, as is usually the case. If possible, the machine should be shut down instantly when any indication of trouble appears, in order to avoid injury and to give time for examination.

Keep Tools Away from Machines. Keep all tools or pieces of iron or steel away from the machine while running. Otherwise, they might be drawn in by the magnetism, perhaps getting between the armature and pole pieces, thus ruining the machine.

Commutator and Brushes. Particular care should be given to the commutator and brushes, so that the former is kept perfectly smooth and the latter are in proper adjustment. Avoid lifting brushes when machine is operating, unless there are several brushes in parallel.

Bearings. Touch the bearings occasionally to see whether or not they are hot. Thermometers embedded in putty will assist in detecting undue temperature rise.

Overloading. *Special care* should be observed by anyone who runs a generator or motor, to *avoid overloading* it, because this is the cause of most of the troubles which occur.

Personal Safety. The matter of personal safety is of great importance in the installation, care, and management of dynamo-electric machinery, both from the humanitarian and from the financial standpoint.

Precautions in Handling the Circuit. The safest rule is never to touch any conductor carrying current, and never to allow the body to form part of an electric circuit, no matter what the voltage. This, of course, is a rule which cannot be followed strictly in practice. However, every precaution should be taken to prevent accidents, and every device which adds to the personal safety of the men should be employed. Rubber gloves, rubber shoes, or both, should be used in handling circuits of 500 volts or over. Also these articles should be tested frequently. Tools with insulated handles, or a dry stick of wood, should be used instead of the hand for handling the wires. It should always be remembered that a wire may be "alive" through some unknown change in connection or through accidental contact with another wire, even when it is thought to be "dead."

High Voltages. On the high alternating-current voltages now so common, even the above precautions are not sufficient. No work can ever be done on such circuits unless they are entirely disconnected from all sources of power. In addition, the wires should be thoroughly grounded before being touched. In grounding, the ground connection should be first made and last disconnected.

Stopping Generators. *Operating Alone.* A generator operating alone on a circuit can be slowed down and stopped without touching the switches, brushes, etc., in which case the current gradually decreases to zero. Then the connections can be opened without sparking or any other difficulty.

Operating in Parallel. However, when a generator is operating in parallel with other sources of power, it must not be stopped until it is entirely disconnected from the system. Furthermore, the current generated by it should be reduced nearly to zero before its switch is

opened. For alternating-current generators, the load is reduced by adjusting the engine governor to reduce the input. The setting of a field rheostat should not be changed.

Never, except in an emergency, should any circuit be opened when heavily loaded; the flash at the contact points, the discharge of magnetism, and the mechanical shock are all decidedly objectionable and destructive.

Stopping Motors. Any alternating-current motor, whether operating singly or with several others on a feeder, may be stopped by simply throwing its manual starter to the "off" position, or by pressing the control "stop" button, if the control is of the magnetic type. No precaution is required before restarting except to be sure that all resistance is reinserted in the secondary of slip-ring motors, and that, in synchronous motors, the field switch is open.

POWER-FACTOR CORRECTION

Low power factor and its consequent evils apply only to alternating-current systems. Power factor may be simply defined as the cosine of the angle by which the current vector leads or lags behind the voltage vector of a given circuit. Although it seldom, if ever, exists, an excessive leading power factor would be as troublesome as a lagging power factor.

Induction motors, induction furnaces, series lighting transformers, and other inductive devices draw a magnetizing component of current which lags behind the line voltage and lowers the power factor of the system. The magnetizing current of an induction motor is nearly constant at all loads with constant voltage. This current lags 90 electrical degrees behind the impressed voltage and does no useful work.

Figs. 36 and 37 show the comparison of magnetizing current, power current, and resultant power factor on a fully loaded and lightly loaded motor. The magnetizing current, *OX*, being practically constant and the power current, *OP*, decreasing from full load to light load, the angle θ increases and the power factor decreases. *OL*, in both cases, represents the current drawn from the line. This illustrates the reason for lower power factor of induction motors at light loads and the necessity of applying motors at near rated capacity.

The effect of low system power factor is far-reaching, in that it increases the size of cables, switches, transformers, and even generators required to deliver a given amount of useful power current. It further affects the system stability by increasing the regulation—that is, impairing the stability of operation, of lines, transformers, and generators. Low power factor imposes an added current load upon all parts of a system with the result that power companies in some localities have rate schedules incorporating a power factor clause which adjusts the rate according to power factor. Other rate schedules allow a bonus if power factor is, for example, above 90 per cent; others

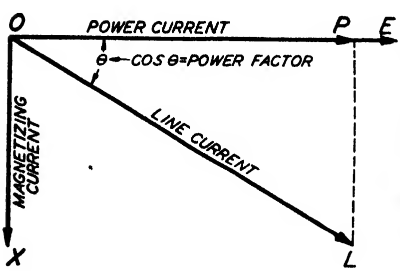


Fig 36 Vector Diagram of a Squirrel-Cage Induction Motor Fully Loaded

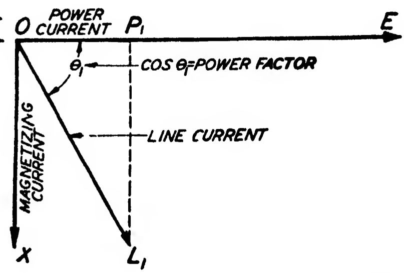


Fig 37 Vector Diagram of a Squirrel-Cage Induction Motor Lightly Loaded

involve a penalty if below 80 per cent; still others specify a flat minimum allowable power factor.

Specific examples will best illustrate the effect of power factor upon line currents. For instance, let us consider a 50-hp., 1,800-r.p.m., 220-v, 60-cycle induction motor which has a full-load efficiency and power factor of .90 and .91 respectively. At full load, its line current will be $\frac{50\times746}{220\times\sqrt{3}\times.90\times.91}=120$ amperes. A similarly rated unity (1.00) power factor synchronous motor with full-load efficiency of 91.4 per cent would draw a line current equal to $\frac{50\times746}{220\times\sqrt{3}\times.914}$, or 107 amperes exclusive of exciter and rheostat losses.

This comparison, although using a fully loaded, high-efficiency, and relatively high power factor induction motor, illustrates a line current requirement 12 per cent higher for the induction motor than for the synchronous motor. Further, let us assume a 440-v, three-phase power circuit carrying a load of 500 kw at .80 power factor.

The resultant line current is $\frac{500{,}000}{440\times\sqrt{3}\times.8}=820$ amperes. If the power factor could be raised to unity (1.00) through the use of synchronous motors or other corrective equipment, the same line could carry $820\times440\times\sqrt{3}=625$ kw—an increase of 25 per cent in power with the same line current. Conversely, if the power factor should remain at .80 as originally, the system would require 25 per cent more copper, transformers, and generating capacity to produce the same output (625 kw) as could be secured by installing power factor correction equipment.

A more severe condition of original system power factor and its improvement to .95 power factor is illustrated by the following chart,

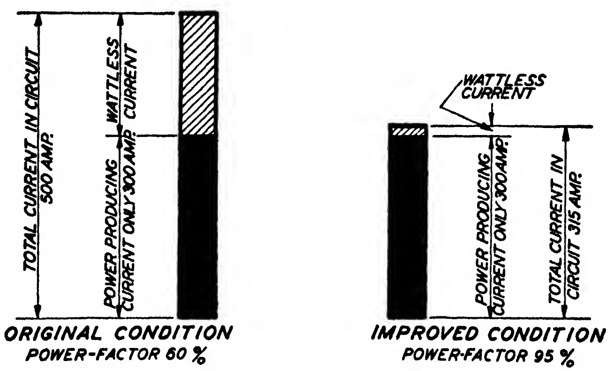


Fig. 38. Chart Showing Result of Adding Power-Factor Correction Apparatus

Fig. 38, which indicates reduced current demand from the power lines for a given amount of kw load at higher power factor.

Methods of Correcting Power Factor. Referring to Fig. 36 it is evident that if it is possible to counteract the lagging component of reactive current (magnetizing current) by introduction of a leading component of reactive current, the resultant angle θ between power current and line current will be diminished and cosine θ or power factor will be increased.

Fig. 39 illustrates the effect of adding leading reactive current to the system. A number of methods are available to accomplish this desired result, as follows:

1. Substitution of synchronous motors for existing induction motors.

2. Use of synchronous motors for additional load requirements.
3. Installation of synchronous condenser.
4. Use of power factor corrective motors, such as Noel capacitor motors and Fynn-Weichsel motors.
5. Installation of capacitors (static condensers).

Under *Methods One (1) and Two (2)*, the use of unity power-factor synchronous motors would increase the average power factor of the

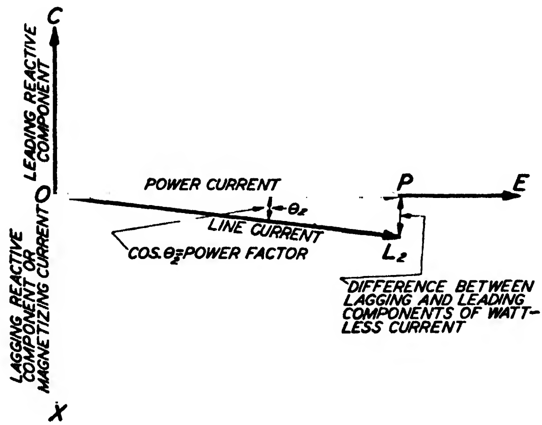


Fig. 39 Diagram Showing How a Leading Reactive Current Improves the Power Factor

system load without adding corrective leading kva. However, if leading power-factor motors are used, they will deliver to the system leading reactive kva equal to $\frac{.746 \times hp.\ rating}{Efficiency \times P\text{-}F}\sqrt{1 - P\text{-}F^2}$, in which power factor is expressed as a decimal.

Method Three (3). A synchronous condenser is simply a synchronous motor running on the line without shaft load and supplying leading current to the line. By varying the excitation the amount of leading kva can be changed at will. This system of correction is not used on low-voltage distribution systems ordinarily. It is more economical to use a synchronous motor partly loaded and excited to run at .70 to .80 leading power factor, enabling both a power load and wattless leading kva to be derived from the same unit.

Method Four (4). The Noel capacitor motor is a standard, squirrel-cage induction motor except that in the bottom of the stator slots there is placed a separate three-phase winding which is connected to a

three-phase capacitor. This capacitor winding is so designed that with 220 or 440 volts applied to the main winding, 600 volts is impressed upon the capacitor by transformer action with the capacitor winding. Therefore, this motor operates at near unity power factor.

The Fynn-Weichsel motor is a form of synchronous induction motor. The rotor is wound with two windings—one, the power winding, fed through slip rings, and the other, an exciting winding which delivers power to a commutator. The stator is also furnished with two windings—one functions similarly to a regular slip-ring motor secondary winding; the other receives the commutated current from

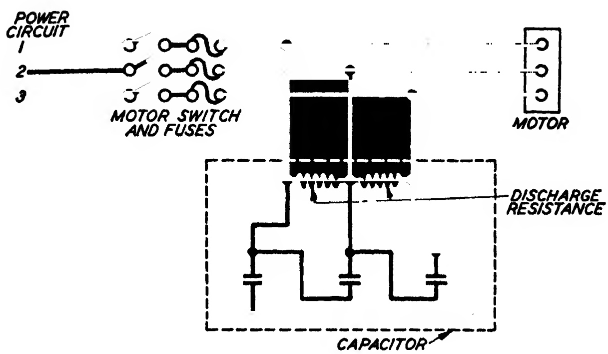


Fig 40 Connection Diagram of Enclosed Capacitor Unit Installed at Motor Terminals

the commutator and excites the motor in much the same manner as do the poles of a synchronous motor. This motor starts similarly to a slip-ring induction motor, but assumes synchronous characteristics at full speed. This type of motor should be applied on a load which remains as nearly constant as possible and at near rated capacity since it is designed to give maximum power factor correction to rated load.

Method Five (*5*). Capacitors are adaptable for installation wherever it is desired to raise the power factor, at the individual motors (Fig. 40), at distribution points feeding a group of motors with relatively short feeders (Fig. 41), or at the main switchboard to improve the combined power factor of the entire distribution system (Fig. 41). They are available in small individually mounted units, or in larger rack-type equipments for operation on circuits from 230

volts to 6,900 volts, and in enclosures suitable for mounting indoors and out of doors. See Figs. 42, 43, and 44.

Capacitor Calculations. Let us assume that it is desired to calculate the size of capacitor necessary to improve the power factor

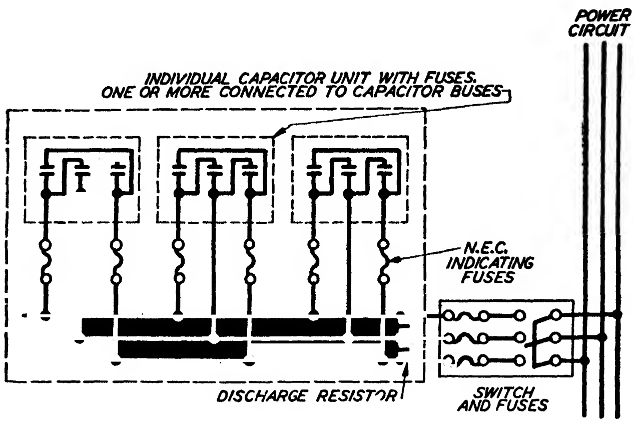
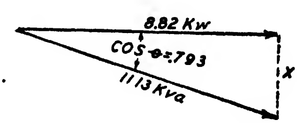


Fig 41 Connection Diagram of Capacitor Installed in Power Circuit

of a 10-hp. 900-r.p.m. induction motor to unity. The full-load efficiency and power factor of this motor are 84.6 per cent and 79.3 per cent respectively. The kw input to the motor is $\dfrac{\text{hp.} \times .746}{\text{Efficiency}} = \dfrac{10 \times .746}{.846}$ $= 8.82$ kw. The kva input to the motor is $\dfrac{\text{kw input}}{\text{power factor}} = \dfrac{8.82}{.793} = 11.13$ kva. By the use of trigonometry, we can determine the value of reactive lagging kva, x, as follows:

$$x = \sqrt{11.13^2 - 8.82^2} = 6.8 \text{ kva.}$$



Therefore 6.8 kva of leading reactive kva must be supplied by a capacitor to neutralize the lagging component and produce unity power factor.

The size of capacitor required to raise the power factor of a given load to a higher value can be found easily, as in the following example:

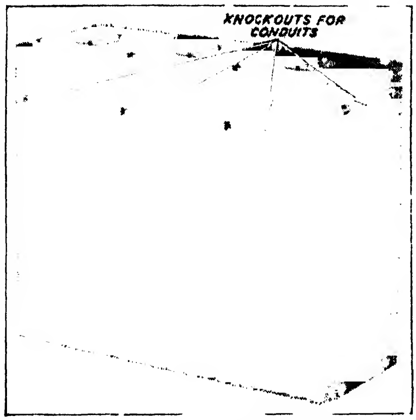


Fig 42 Three-Phase 60-Cycle Enclosed Capacitor Unit (3-Kva 230-Volt)

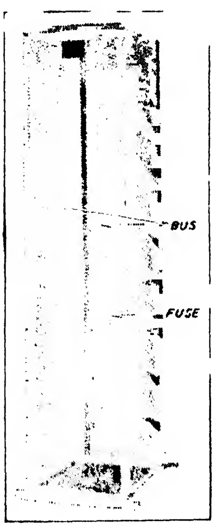


Fig 43 Three-Phase, 60-Cycle Indoor Rock-Type Capacitor Unit (120-Kva, 460-Volt)

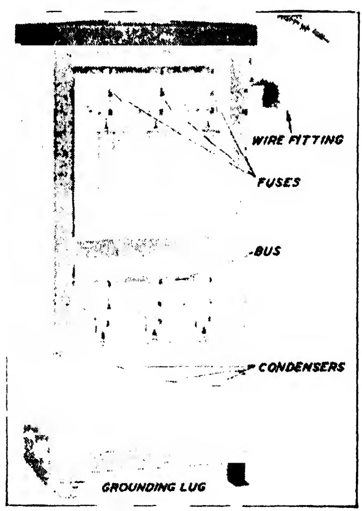


Fig 44 Three-Phase, 60-Cycle Outdoor Capacitor Unit, Side Removed (60-Kva, 460-Volt)

Assume it is desired to raise the power factor of a 300-kw load from 60 per cent to 90 per cent.

A 300-kw load at 60 per cent power factor has an apparent load of $\frac{300}{.6}$ or 500 kva, and has a lagging component of $\sqrt{500^2-300^2}$, or 400 kva.

A 300-kw load at 90 per cent power factor has an apparent load of $\frac{300}{.9}$ or 333 kva, and has a lagging component of $\sqrt{333^2-300^2}$, or 145 kva.

The difference between the two lagging components (400 − 145) is 255 kva and is the leading kva that will be necessary to raise the power factor to 0.90.

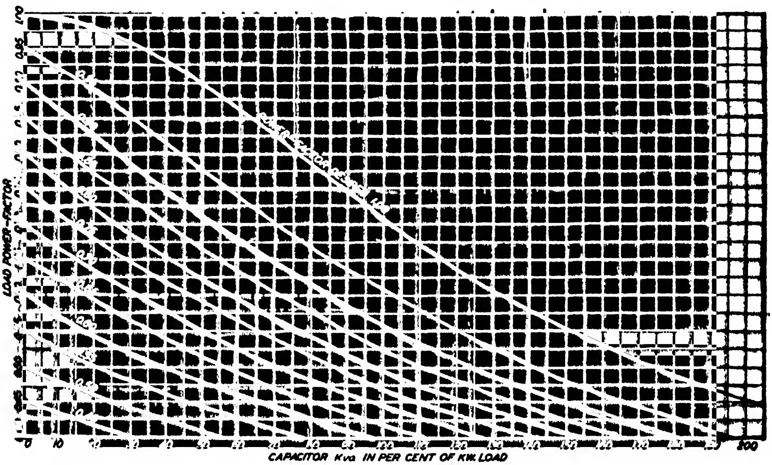


Fig. 45. Curve Showing Capacitor Required to Give Desired Power-Factor Improvement

Determination of capacitor required to give desired correction in power factor Follow horizontal line corresponding to present power factor of load until it intersects curve representing power factor desired. The vertical projection of this intersection on the base gives the size of capacitor required in per cent of kw. load.

Example.—Load 300 kw. Present power factor 60 per cent, power factor desired 90 per cent. Projection of intersection of 60 per cent power factor line with 90 per cent power factor curve gives desired capacitor as 84.9 per cent of 300 kw., or 255 kva.

To simplify these calculations, factors by which the kw load can be multiplied to give the size of capacitor necessary can be taken directly from the curves in Fig. 45.

Each method of power factor correction has its field of application and it is possible that a combination of at least two types of corrective equipment can be selected for each plant or building. However, correction by capacitors appears to be the most acceptable method, for the following reasons:

1. They can be installed in any location without disturbing existing equipment.

2. Corrective capacity can be selected at will, with no dependence upon operating conditions, such as continuity of load.

3. Capacitors produce their corrective effect every moment they are connected to the line, and since they are static, i.e., have no moving parts, there is little likelihood of necessity for repairs.

STARTING AND CONTROLLING DEVICES FOR ALTERNATING-CURRENT MOTORS

Starters and controllers for alternating-current motors normally include all switches and contactors necessary for controlling the starting operation and speed regulation (where required) plus thermal overload devices to protect the motor against normal overload. All parts are of adequate capacity to break the normal overload or stalled current of the motors to which they are connected, but are not designed to interrupt short-circuit currents which may be caused by grounded or short-circuited wires and cables. Circuit-interrupting devices such as fuses, air circuit breakers, or oil circuit breakers of adequate interrupting capacity should be installed ahead of the control equipment to protect feeder lines and control, and also to meet Underwriters' and Code requirements.

All circuit diagrams shown hereafter in this section are standard, as used by the General Electric Co., and are shown to be illustrative of general types. All diagrams are used by courtesy of the General Electric Co.

Single-Phase Motor Starters. Single-phase motors may be started and adequately protected against overload by manual or magnetic two-pole switches, with one overload coil. The only exception is in the case of the high-torque capacitor motor which requires a third pole to disconnect the running capacitor.

Polyphase Motor Starters and Controllers. *Squirrel-Cage Induction Motors.* For small sizes, manually operated starters with two-coil overload protection are available. These do not provide undervoltage protection or facility for remote control by push-button, or pilot control such as float switch and pressure switch. Fig. 46 illustrates connection of a magnetic across-the-line starter for constant-speed motors.

Fig. 47 shows the circuit of a magnetic reversing switch for squirrel-cage motors.

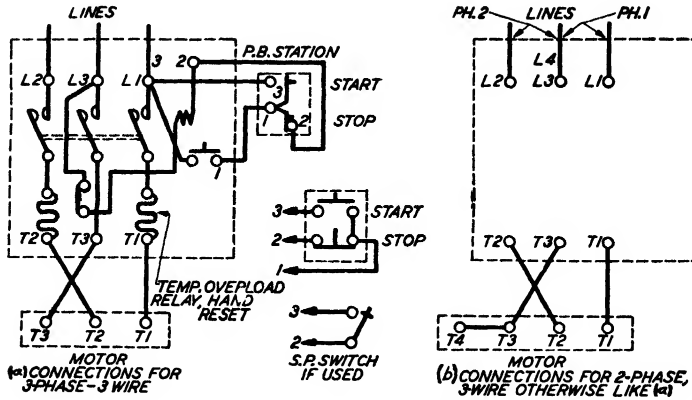


Fig. 46. Connection Diagram for Across-the-Line Magnetic Starter

Pressing the push button marked *Start* allows current to flow from line *L1* to contacts *3* and *2*, through the contactor coil and the temperature overload relay contacts to line *L3*. This causes the contactor to close, connecting the motor terminals *T1*, *T2*, and *T3* directly to the line wires *L1*, *L2*, and *L3* respectively.

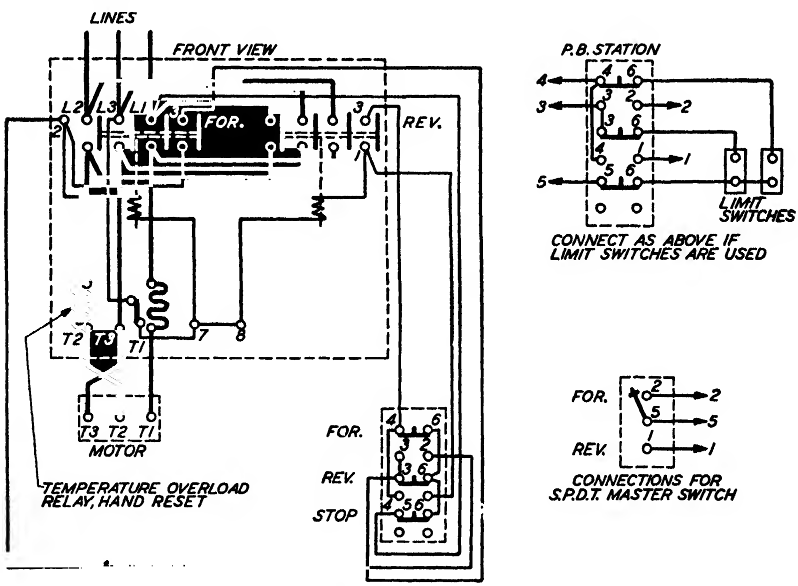


Fig. 47 Connection Diagram for Reversing Magnetic Controller

Pressing the *For.* button allows current to flow from line *L1* to *Stop* and *Rev.* buttons, contacts *3* and *2*, terminal *2* near the forward contactor, through the *For.* contactor coil, terminal *7*, temperature overload relay contacts to *L3* This closes the forward contactor, at the same time forming a circuit across contact *3* of the contactor, which allows current to flow from terminal *3* on the *Rev.* button through to terminal *2* near the forward contactor, through that contactor coil, holding it closed when the *For.* button is released and returned to the position shown. Pressing the *Stop* button opens the circuit of the *For.* contactor coil, allowing that contactor to open. Then the reverse button can be pressed and a flow of current will close the *Rev* contactor in a similar manner.

Fig. 48 illustrates connection of a typical manually operated reduced-voltage autotransformer type starter for squirrel-cage induction motors.

Fig. 49 illustrates magnetically operated one-step primary-resistance type of induction-motor starter.

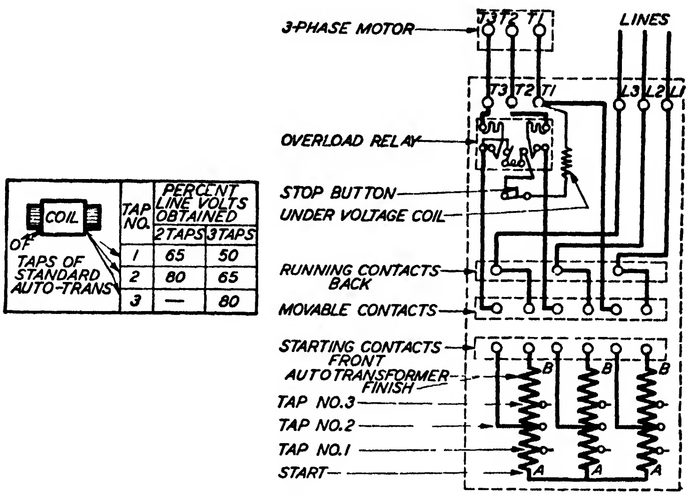


Fig 48 Connections for Manual Autotransformer Reduced Voltage Starter

Standard compensators up to 50 hp have two taps and those above 50 hp have three taps. Moving the handle of the compensator to the *Start* position causes the group of movable contacts, indicated within the dotted rectangle, to move down on top of the starting contact Current then flows from line wires *L1*, *L2*, and *L3* directly to the upper terminal *B* of the autotransformer, through it to the Star connection at *A* Tap No 2 of each coil is connected to motor terminals *T1*, *T2* and *T3* respectively When the handle is pushed to the running position, the movable contacts slide over on top of the running contacts, connecting lines *L1*, *L2*, and *L3* directly to the motor terminals *T1*, *T2* and *T3* The compensator handle is held in the running position by means of a catch that can be tripped by the plunger of the under-voltage coil The overload relay as well as the stop button can open the under-voltage coil circuit and trip out the compensator, allowing the movable contacts to return to the position shown in the diagram

Fig. 50 shows wiring connection for a magnetically operated, reduced-voltage, autotransformer type starter.

It would be difficult to show the many types of connections required for multispeed squirrel-cage induction motors, because of the many different motor winding connections required for different torques. Therefore, only Fig. 51 is shown to illustrate a magnetic controller for a typical two-winding, two-speed induction motor, requiring the simplest type of control.

Manually operated drum controllers are also used for multispeed motors. In most instances, especially for constant-torque and con-

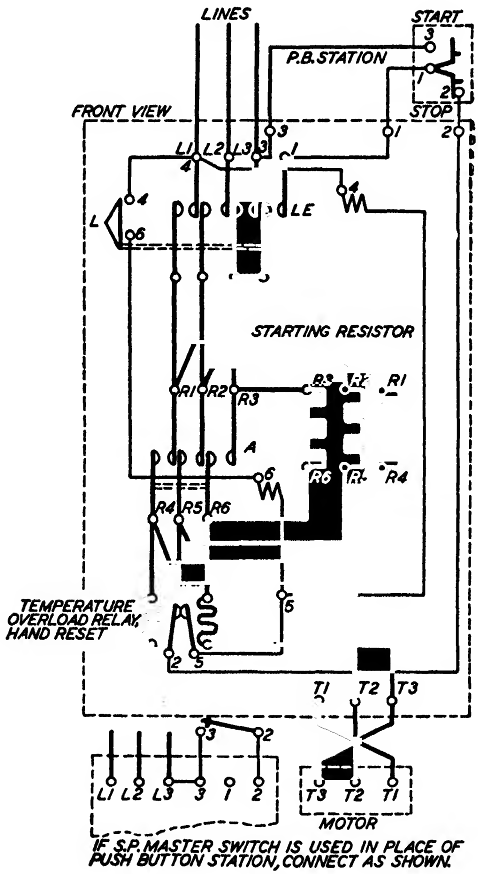


Fig. 49. Connections for Primary Resistor Type Starter

Pressing the *Start* button allows current to flow from *L1* to the line contactor coil *4*, through temperature overload relay contact *5* to *2*, through the push button, terminals *2* to *3* to line *L3*. This closes the line contactor *LE*, to lines *L1*, *L2*, and *L3*, through the starting resistor *R1-R4*, *R2-R5*, *R3-R6*, respectively, to the motor terminals *T1*, *T2*, and *T3*. Then when the timing relay *L* closes contacts *4* and *6*, current flows through coil *6* of contactor *A*. This short-circuits the starting resistance, connecting the motor directly to the line.

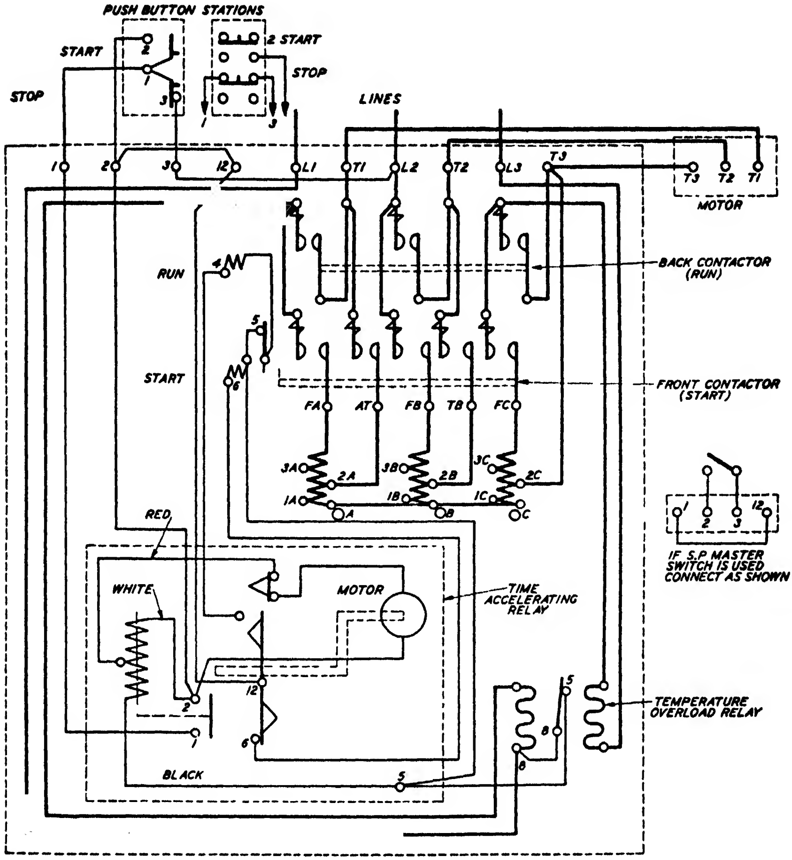


Fig. 50. Wiring Diagram for a Magnetically Operated Autotransformer Type Reduced Voltage Starter

Pressing the *Start* button allows current to flow from *L1*, through the temperature overload relay contact *8* to *5*, through the start contactor coil *6*, through the time accelerating relay contact *12*, to terminals *12* and *2* of the start button, through the push button to terminal *3* and line *L2*. Current flowing through the contactor coil *6* causes the *Start* contactor to close, connecting the lines *L1*, *L2*, and *L3* to the autotransformer coils *FA*, *FB*, and *FC*. These three coils are Star connected at points *A*, *B*, and *C*. The taps *2A*, *2B*, and *2C* are connected to motor terminals *T1* and *T2* through the contacts *AT*, and *TB*. The tap on coil *C* is connected directly from *2C* to terminal *T3*. When the *Start* push button is pressed, current also flows from line *L1* to temperature overload relay contacts *8* and *5*, through terminal *5*, through the timing relay coil to *2*, and to terminal *2* of the push button. This closes contacts *1* and *2* at the timing relay and applies voltage to the motor of the timing accelerating relay. This voltage is from the middle point on the coil below the word *White* and terminal *2*. Current going through the coil closes contacts *1* and *2*, establishing the holding circuit when *Start* button is released. When the motor of a timing accelerating relay operates, it opens contacts *12* and *6*, allowing the start contactor to return to the open position, closing the interlock *5* above contactor coil *6*. At the same time the motor closes the contacts *12* to *4* of the running contactor coil, allowing current to flow through that coil and closing the running contactor. The motor terminals *T1*, *T2*, and *T3* are connected directly to the line terminals. Taps on autotransformer are similar to those shown in left-hand view, Fig. 48.

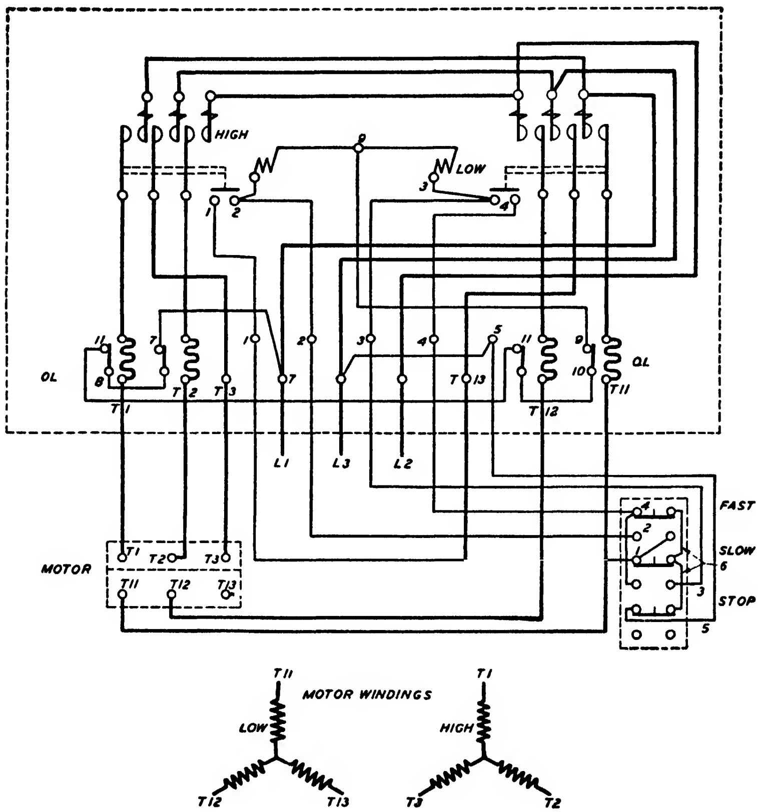


Fig. 51. Magnetic Controller Connections for Two-Speed Squirrel-Cage Induction Motor

This motor has two separate windings. The high-speed terminals are *T1*, *T2*, and *T3*. The low-speed windings are *T11*, *T12*, and *T13*. Pressing the slow speed button joins wires *3* and *4* at the push button, forming a circuit from *L1*, terminals *7*, *8*, *11*, right-hand overload relay, terminals *11*, *10*, *9*, to the low-speed contactor coil, to terminal *3* at the push button, through the *Fast* button *4*, wire *6*, stop button, wire *5*, terminal *5* to *L3*. This causes the low-speed contactor to close, connecting *L1*, *L2*, and *L3* directly to the motor terminals through the overload relay coils *OL* to motor terminals *T11*, *T12*, and *T13* respectively. When changing to high-speed, pressing the push button marked *Fast* causes current to flow from terminal *9* through the high-speed contactor coil, terminal *2* to the push button, terminal *1*, through the low-speed button terminal *6*, through the *Stop* button, wire *5*, terminal *5* and *L3*. This closes the high-speed contactor, joining the main lines *L1*, *L2*, and *L3* directly to the motor terminals *T1*, *T2*, and *T3*, through the overload relay coil and line wires *T1* and *T2*. When either the high-speed or low-speed contactor closes, contacts *1* and *2*, and contact *4* of the low-speed contactor are connected, holding that particular contactor closed when the fast or slow button is released.

stant-horsepower motors, an overload device is provided for each operating speed.

Control for Wound-Rotor Induction Motors. Fig. 52 shows the circuit of a manual-dial type secondary starting rheostat with inter-

locked primary magnetic switch, for small motors up to 20 horsepower. Since the primary switch cannot be closed until the interlock is closed, with the dial in "Resistance In" position, it is impossible to start the motor with the rings short-circuited.

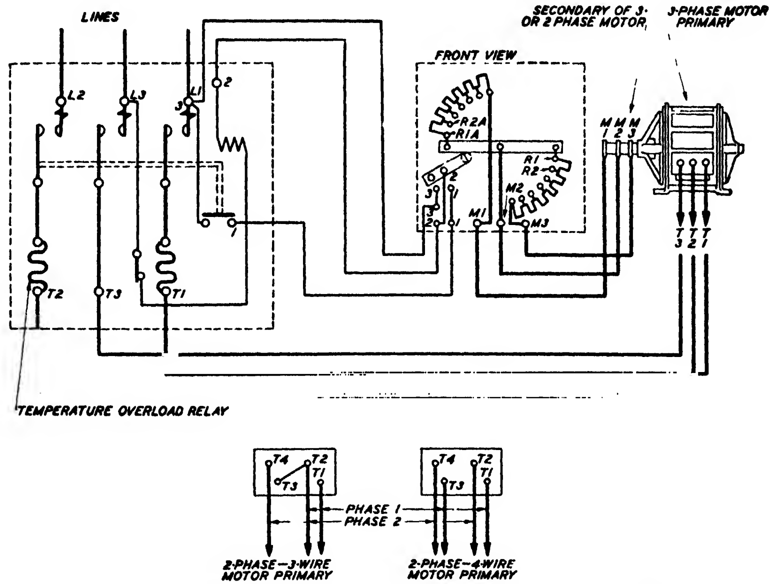


Fig. 52. Wiring Connections for Starting Small Slip-Ring Induction Motor

Pushing the small lever down on the front view of rotor resistance controller joins contacts *2* and *3*, allowing current to flow from *L1*, through contacts *3* and *2*, line contactor coil, temperature overload relay contact, to line *L3*. This closes the contactor, joining *L1*, *L2*, and *L3* through the temperature overload relay to the motor terminals *T1*, *T2*, and *T3*. When the contactor closes, *L1* is joined to control terminal *1*, thus providing a holding circuit through the contactor coil. The speed of the motor is increased by moving the rheostat bar *R1A* and *R1* clockwise, decreasing the resistance between the rotor leads *M3* and *M2* and also between *M1* and *M2*.

A simple, manually operated, dial-type control with secondary resistor for speed-regulating duty is illustrated in Fig. 53. The push-button station may be omitted and the interlock switch wired direct to the primary magnetic switch coil, if desired.

Larger motors whose secondary current per phase exceeds 100 amperes require manually operated drum switches. Fig. 54 shows connections, using either a primary magnetic switch or a primary oil circuit breaker. Both combinations use an interlock circuit to primary switch, requiring all resistance to be inserted in motor secondary before primary switch can be closed. The same wiring is used

for both starting duty and speed-regulating duty, the only difference in equipment being the resistor which is heavier duty for the continuous service required in speed-regulating duty.

Magnetically operated starters are also available for slip-ring motors, see Fig. 55. If such a control is required for speed-regulating duty, the number of contactors is increased to give more speed points, the resistor is changed to speed-regulating type, and a multi-button push-button station and additional interlocks on each contactor are

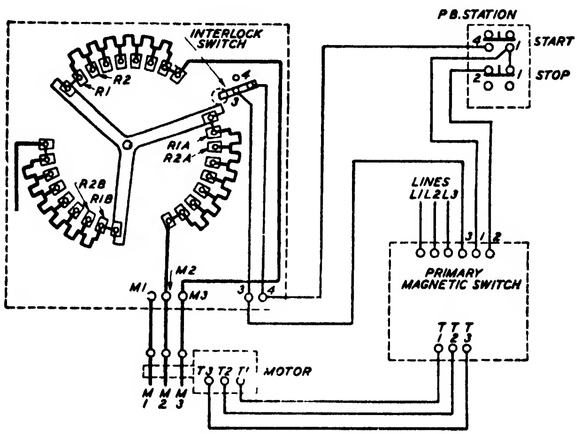


Fig. 53 Manual Speed-regulating Control for Small Slip-Ring Induction Motor

The internal connection of the primary magnetic switch is similar to Fig. 46. The speed of the motor is increased by moving the Y arm clockwise. This decreases the amount of resistance across the slip rings *M1*, *M2*, and *M3* of the motor

used to give pre-set control. When any speed button is pressed, the control will automatically accelerate to that point and run at the pre-set speed.

Control for Synchronous Motors. Fundamentally, the same elements of control must be provided for a synchronous motor as are used with alternating-current generators, namely: main-line switch, field switch and discharge resistor, and a field rheostat. When starting a motor with this simple control, certain precautions must be exercised to insure synchronization without damage to motor or undue disturbance to line. The field switch is open, with the motor field shorted across the discharge resistance. The first operation is to close the main switch. The motor will then accelerate up to near synchronous speed, as does an induction motor. Then the field switch is

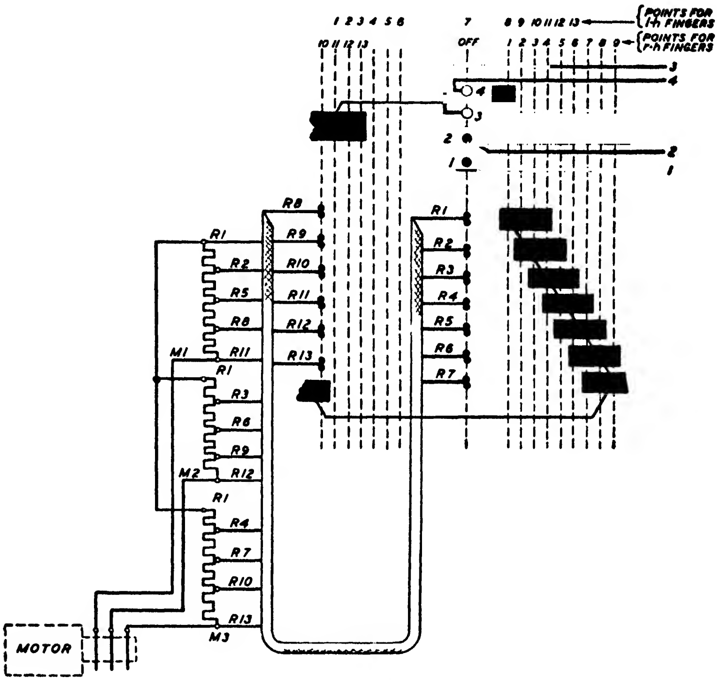


Fig. 54. Non-reversing Drum Switches and Resistors for Wound-Rotor Induction Motors with Three-Phase Secondary

This type of drum controller can be used with a primary magnetic switch like Fig. 46 or with a circuit breaker. When used with a magnetic switch, fingers *2*, *3*, and *4* are used. With a primary oil circuit breaker, only fingers *1* and *2* are used to provide a magnetic lock on the circuit breaker. There is no electrical connection between these four fingers and those marked *R1*, *R2*, etc. The purpose of the drum controller is to decrease the amount of resistance in steps *R1*, *R2*, *R1–R3*, *R1–R4*, then decrease the resistance *R2–R5*, etc. For tracing the circuits where the wires enter a cable, they have a similar letter and number when leaving that cable to the finger. The heavy black line represents the disks on the drum controller and the black double circle represents the fingers. The handle on the drum controller rotates the segments for the different points, of which there are 13. Each point cuts out one step of resistance in the rotor circuit, first in one phase and then the other.

closed, causing the motor to be excited as a synchronous machine, and it will pull into step or synchronism. The field excitation may then be adjusted to the required value to produce unity or leading power factor operation. If autotransformer, reduced-voltage starting equipment is used, the same procedure is followed except that the motor is accelerated on the starting step and then thrown to the full-voltage position and allowed to pull up to speed before closing the field switch and synchronizing.

Manual starting, as described, requires attendance on the part of an operator and supervision of the subsequent operation to insure

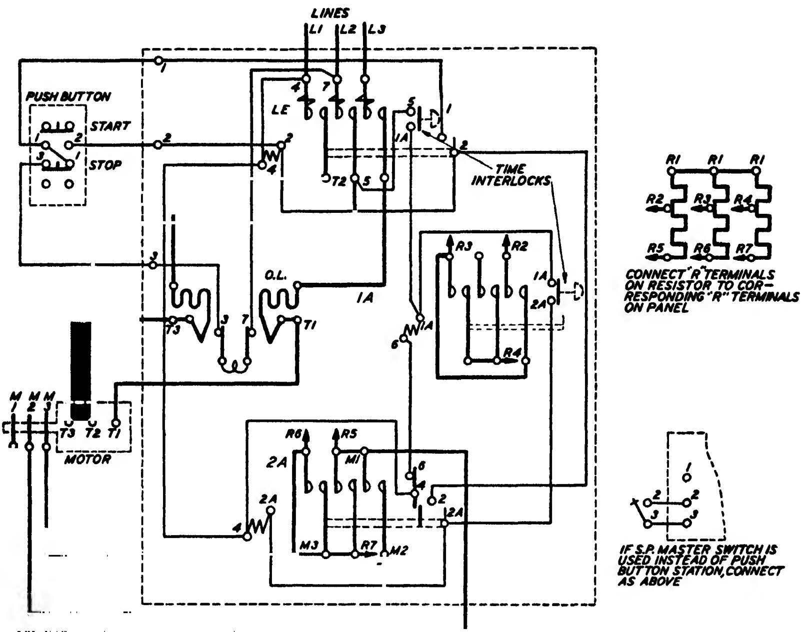


Fig. 55. Magnetic Control for Slip-Ring Induction Motor

This controller starts the wound-rotor induction motor with all the resistance in the motor circuit the first step, then half the resistance cut out and finally all of the resistance cut out of the rotor circuit. This can be accomplished by pressing the *Start* button, which allows control current to flow from *L3* to terminal *4*, through line contactor coil *LE*, contact *2* of the push button, across the push button terminal, to the stop-button terminal *3*, to the *OL* contacts *3* and *7* to line *L2*. This closes the contactor *LE*, connecting lines *L1*, *L2*, and *L3* to the motor terminals *T1*, *T2*, and *T3*, through the overload relay coil. The contactor also closes contacts *1* and *2* at the right-hand end of the contactor and sets the time interlock in operation. After a set time the time interlock *5-1A* will close those contacts. This allows current to flow from line *L3* to terminal *4*, through the interlock contacts *4* and *6*, contactor coil *1A*, contacts *1A* and *5*, to line *L2*. Closing the contactor *1A* joins the terminals *R2*, *R3*, and *R4* of the resistor shown at the right, which short-circuits or cuts out of the circuit resistance *R1-R2*, *R1-R3*, and *R1-R4*.

After a brief time interval the time interlock at the right of contactor *1A* closes, allowing current to flow from line *L3*, control terminal *4*, to contactor coil *2A*, through the contact *2A* of the time interlock to *1A*, through *1A* of the time interlock on the contactor *LE* to line *L2*. This causes contactor *2A* to close. This joins resistance *R5*, *R6*, and *R7* together. This has the effect of cutting out all the resistance, or the same as short-circuiting the rotor leads *M1*, *M2*, and *M3* of the motor. When contactor *2A* closes, the lock-in contact *2* and contact *2A* on the dotted line establish a holding circuit through contactor coil *2A*. At the same time the interlock contacts *4* and *6* are opened, allowing contactor *1A* to open.

proper protection of the motor. Modern synchronous-motor control has been developed to the point where only an initial starting operation is required, such as pushing a "start" button if fully magnetic, or operating the main starting switch if semimagnetic. Subsequently and at the proper time, field application is accomplished automatically by control and timing devices. Thus an operator is relieved of the responsibility of determining sequence and timing.

UNIVERSAL MOTORS

Universal motors are motors which are designed for operation on either alternating-current or direct-current circuits of the same voltage. Their largest field of use is in operating household appliances, such as sewing machines, vacuum cleaners, electric fans, etc. They usually form a part of some appliance which requires a small amount of power, and the sale and use of that appliance is made easier by having a motor which will operate on both alternating current and direct current. They are generally wound for use on 115-volt circuits, and are always of the series type, that is,

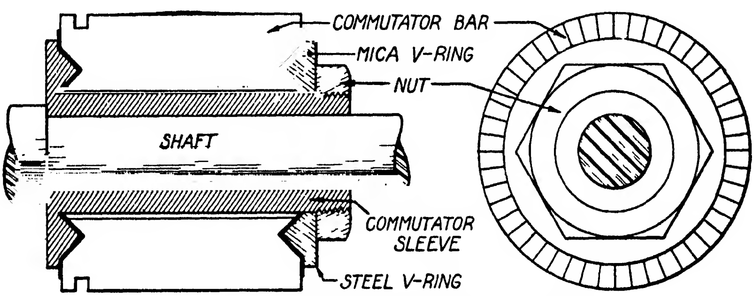


Fig 1 Interior View of Construction of a Commutator

the armature and field coils are connected in series. In many cases, the outside of the motor or the housing forms part of the appliance or machine which it operates.

There are some universal motors built that are operated in connection with electric railway systems where on part of the road the power supply is alternating current and on the other part, as in the towns and cities, direct current is used. These railway motors and other universal motors over one-half horsepower in size have special windings and will not be considered here. Rather, this discussion will be on motors having a rating of one-half horsepower or less.

Construction

The armature construction of universal motors is the same as for small fractional horsepower direct-current motors. The

diameter of the armature usually varies from about $1\frac{1}{2}$ inches to about $3\frac{1}{2}$ inches. The commutators are pressed on the shaft by a small press, designed to force them in position. In the better grade of universal motors, the commutators are assembled as shown in Fig. 1. In the more cheaply constructed machines, instead of a threaded nut being used to clamp the V-ring to the sleeve, the commutator bars, mica, steel V-rings and the commutator sleeve are placed in a special designed press which clamps them very tightly, and then the threaded part of the commutator sleeve, Fig. 1, is riveted tightly over the right-hand steel V-ring.

Armature winding

Very small copper wire is used in winding the armature coils on these motors. Nearly all manufacturers use an automatic

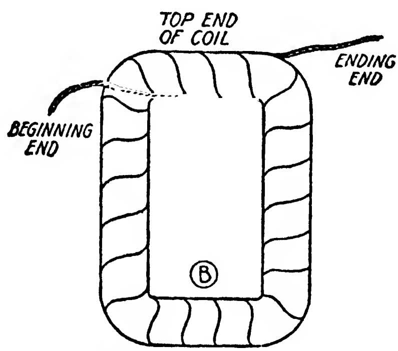


Fig. 2. Construction of Field Coil

machine which winds the desired number of turns of wire directly into the slot. Enamel insulated magnet wire is very generally used for the armature winding. In a few cases, however, enamel insulated magnet wire with a wrapping of silk or cotton thread is used. This is known as single-silk enamel or single-cotton enamel insulated magnet wire.

Field coils

The field coils are wound on a form by a machine to the correct dimension and then are covered with a half lapping of cotton tape, Fig. 2. These field coils are usually composed of a large number of turns of very small enamel insulated magnet wire. Thus on a

115-volt motor, there may be between 250 to 500 turns of wire of a size between No. 30 to No. 40. No. 40 wire is about as thick as a sheet of paper in this book.

Stator core

In universal motors a laminated iron core must be used instead of a solid iron core as with direct-current motors. The reason for this is that with alternating current, you have the current reversing its direction of flow many times every second. Every time the current reverses its direction of flow the iron core is magnetized and demagnetized in the opposite polarity. A solid piece of iron will not magnetize or demagnetize as rapidly as a piece which is composed of a number of thin sheets riveted together, forming a

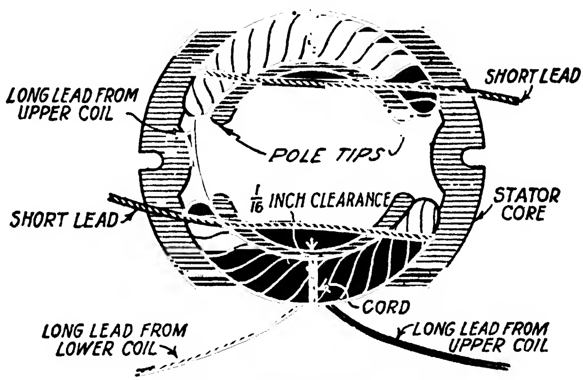


Fig. 3. Stator Core with Field Coils in Place

laminated iron core. Moreover, when magnetizing and demagnetizing an iron core, an electromotive force or voltage is produced in the iron core; and the faster the core is magnetized and demagnetized, the greater will be this voltage that is generated or produced. When a solid iron core is used, this induced voltage causes electric currents to flow around through the solid iron core. These electric currents are called eddy currents. These eddy currents heat the iron core and produce magnetism that opposes that produced by the alternating current. In order to overcome this trouble from eddy current, the cores are built up of thin sheets of steel that are cut or punched to the desired shape, as shown in Fig. 3. These

thin sheets of steel are riveted together into a solid block, which is fastened inside the housing of the frame of the motor.

The field coils are slipped in position back of the pole tips, Fig. 3, and then the center of the coil is pulled upwards and is often pressed or held in place by the use of cords or sometimes by a metal strap.

The stator core with assembled field coils is often held in the housing by passing bolts or screws through the slots or holes in the core and clamping or fastening the two parts of the housing together, Fig. 4.

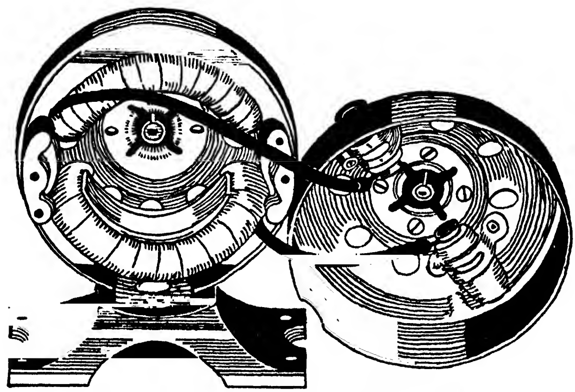


Fig 4 Stator Core Assembled in Housing of Motor

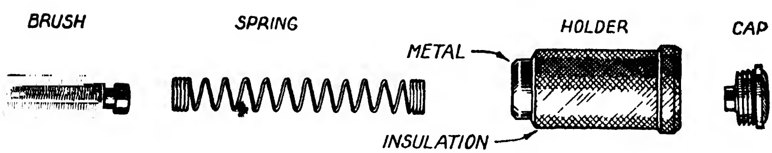


Fig 5 Parts of Brushholder Mechanism

Nearly all universal motors use only two carbon brushes, which are mounted on opposite sides of the housing. These brushes are usually either round or square and are held against the commutator bars by the use of a small spring, Fig. 5. They usually are held in position on the commutator by means of a brush holder, which is placed inside a tube of insulating material. The insulating material is clamped, riveted, or fastened in some other manner to the housing of the motor. A threaded cap usually fits into the end

of the brass tube. The leads from the field coils or line wires are usually soldered to the edge of the brushholder on the inside of the housing, although in some motors these connections are made on the outside of the housing to the cap screw at the end of the brushholder.

Operating instructions

Since a universal motor will operate on both direct-current and alternating-current circuits, it is necessarily equipped with a commutator, and thus requires more attention than an induction motor. In order to keep a universal motor in proper running condition, it is necessary to carry out the following instructions:

(1) Inspect the motor at least once a day, if it is located in an industrial plant where motors are inspected regularly.

(2) Keep the motor free from lint and other foreign material.

(3) See that the bearings are not leaking and allowing the oil to get to the winding and commutator.

(4) See that the brushes are free to move and are not stuck in the holders. (This condition is caused from an accumulation of copper and carbon dust and oil gumming up the brushes and holders and is the most common cause of arcing between the brushes and commutator.)

(5) See that the commutator is clean and true. On some types, the mica of commutator should be slightly undercut.

(6) See that windings do not overheat due to overload or other cause.

(7) See that the belt is properly lined up between motor and load.

(8) See that the lacing or belt clips do not make a bulge in the belt and cause slapping on the pulley when passing over it.

(9) Change the oil or grease in the cups fastened to the bearings at least once every six months.

(10) Blow the dust and dirt out of the motor with a hand bellows whenever it is noticed that there is an accumulation of it.

Truing-up a commutator

After a motor has been used for several years, the commutator usually wears down more where the brushes press against it than at the edges, and in this way grooves or ridges are formed on the commutator; and if the amount of movement of the armature shaft endwise in the bearing changes, due to wear, the brushes will not bear properly on the commutator but will be lifted from it. When this condition occurs, it is necessary to remove these ridges by truing up the commutator. This may be done in a variety of ways. The oldest method, and one which is still used to a considerable extent, is to remove the armature from the motor and have a machinist

place it in a small lathe. While the armature is being rotated rapidly in the lathe, with a cutting tool, which is used in cutting metals in a lathe, take a very fine cut off the face of the commutator. The commutator is polished by holding a piece of sandpaper against its surface while the armature is being revolved in the lathe.

When the housing of the motor is constructed so that it is possible to reach into the commutator while the motor is running, the ridges on the commutator may be removed by the use of a commutator stone, Fig. 6. These commutator stones are made by the Martindale Electric Company, Cleveland, Ohio, and other firms.

Fig. 6. Commutator Stone for Small Motors

When a commutator stone is not available, a small piece of fine sandpaper can be rolled around a small wooden stick and held against the commutator while the motor is running. This process is much slower, because sandpaper will not cut as rapidly as the commutator stone. It should be used only where other methods are not available and the ridges are not very deep.

It sometimes happens that the commutator instead of having ridges is lopsided or out of round. In this case, instead of holding the commutator stone rigidly against the commutator at a constant pressure, it is well only to apply a slight amount of pressure and try to hold it braced against part of the housing so that as the motor is running the high spots on the commutator will be worn down. Then as the high spots are cut down, the pressure can be increased.

Troubles in universal motors

Table I, pages 8 to 13, gives a list of troubles, the symptoms, the causes, and the remedies to apply to the troubles that usually occur on universal motors.

Determining when to repair and when to junk a universal motor

The useful life of any motor does not extend much beyond twenty years, although cases are on record of thirty years of continuous service and even greater. The life of a motor will depend

entirely on the care it has received. There are two cases, however, where it is cheaper to junk a motor than to repair it. These are

(1) When the motor has been through a fire

(2) When the commutator has worn down to such a point that it has exploded due to centrifugal force and completely ruined the brush rigging, armature and field windings. In a case of this kind nothing of any value will remain outside of the frame.

It is cheaper to repair the motor than to buy a new one when only one of the following defects exists. When two or more of these defects exist, then it is cheaper to junk the motor and purchase a new one.

(1) Where a new commutator is needed
(2) Where the armature needs rewinding throughout
(3) Where new field coils are required
(4) Where new brushes and brush rigging are required
(5) Where new bearings are required

Repairing armature windings

Where a minor trouble occurs in the armature or field of a universal motor, it is not always necessary to rewind either of them in order to put the motor back into operation. It has been shown in Table I that flashing at the brushes may be due to a short circuit, but it does not mean that when the armature is short circuited that the replacement of a coil or coils is necessary, since one cause of short circuit is in the accumulation of carbon and copper dust where the armature leads connect to the commutator. Again, heat from the commutator may char the insulation on the leads from the armature winding to the commutator, with the result that these come together and cause a short circuit.

If, however, a short circuit from either of the two foregoing causes is not promptly attended to, a short circuit of two or more complete armature coils will be the result, and in all probability the insulation will be completely charred, not only on the short-circuited coils but also on those adjacent to them.

Again, even if one or more coils are completely ruined, the motor may be made to operate at reduced rating by simply cutting out the defective coils and connecting the remaining coils so that there is a completed circuit through the armature. Care must be taken when cutting out or "jumping" a coil that the connections are properly made and that one or more of the remaining coils are not short circuited.

TABLE I
Troubles of Universal Motors

Symptom	Trouble	Cause	Remedy
1. Bearing too hot to touch, or smoking	(a) Bearing dry	(a) Not sufficient grease, or capillary action of felt wiper retarded on small sizes. Not sufficient oil	(a) Examine and clean felt wiper; refill reservoir with new grease or oil. Clean bearings and refill with fresh oil or grease.
	(b) Bearing dirty	(b) Dust or dirt in oil or grease	(b) Clean out grease or oil reservoir and refill.
	(c) Bearing tight	(c) Lack of lubrication. Undersized bearing, if bearing has been changed	(c) Replenish grease or oil reservoir with more lubricant. Polish shaft with emery paper or replace bearing.
	(d) Bearing binding	(d) Shaft out of true	(d) Place shaft in a lathe and true and renew bearing if worn.
	(e) Bearing out of true	(e) Too much strain on pulley	(e) Renew bearing.
	(f) Loose bearing	(f) Vibration	(f) Tighten set screws holding bearing in housing.
2. Bearing hot, but no hotter than other parts of frame	Heat transferred from armature or field coils	Overload	Decrease load or increase size of motor.
3. Sparking of the brushes	(a) Brushes not set properly with regard to the field winding (NOTE: The brush position on small size universal motors is fixed by the manufacturer and cannot be changed unless the end bell is shifted. On larger sizes, however, they are not always fixed and can be shifted.)	(a) Stator laminations not set properly in frame on some makes; end bell shifted on other makes	(a) This will not happen unless the motor has been taken apart and carelessly assembled. If this has been done, shift the end bells on some types and shift the stator laminations on others of the smaller sizes. On the types where the end bells can be shifted, there are holes through the laminations through which the bolts holding the end bells pass and unless the end bell is put back in its proper place, the brushes will be shifted in relationship to the field coils. (NOTE: The brush position on small size universal motors is fixed by the manufacturer and cannot be changed.) On the types where shifting the stator core affects the brush position, the effects of sparking are overcome by moving the stator to another position in the frame.
	(b) Brushes cover too many bars	(b) Brushes too thick	(b) Use proper brushes or grind those in use to proper thickness. This trouble is seldom encountered unless the brushholder becomes worn or its size has been changed.
	(c) Brushes too short	(c) Wear	(c) Replace with new brushes.

TABLE I—Continued
Troubles of Universal Motors

Symptom	Trouble	Cause	Remedy
	(d) Poor contact between brush and commutator	(d) (1) Oil or grit on commutator (2) Flint or other hard substance in brush	(d) (1) Clean commutator with a dry rag. (2) Sandpaper the brush to remove foreign matter, keeping it in the shape of the commutator. (NOTE. Do not use emery paper or cloth.)
	(e) Rough commutator	(e) (1) Vibration (2) Uneven brushes (3) Different quality of bars (4) Uneven ridges where brushes do not wear the commutator	(e) Place armature in a lathe and true the commutator. On the larger sizes, and if taken in time, the commutator may be trued by means of a commutator stone or a piece of sandpaper.
	(f) (1) High bars (2) Low bars (3) Loose bars	(f) Clamping cone loose. Rough usage of commutator	(f) In the case of high bars, loosen commutator slightly and press bars back into place. With low bars, lift them level with the others. In both cases carefully tighten locknut or set screws and true commutator in a lathe. With loose bars, tighten cones and true the commutator.
	(g) High mica	(g) Copper wears faster than mica	(g) Undercut mica below the surface of bars. Remove all dust before putting back into service.
	(h) Weak magnetic field	(h) Short circuit in field windings	(h) When operating on D. C. current, a short-circuited field coil is cooler than those adjacent to it. On A. C. current, the short-circuited coil is hotter than those adjacent to it and is readily indicated by smoke issuing from it. The only remedy is to replace with a new one. (NOTE: If the short-circuited coil does not show up as outlined above, impress full direct-current voltage across the windings and place the blade of a screwdriver or a nail at the center of each coil. The coil or coils where the magnetic pull is least will be found shorted. Do not leave voltage on the windings for any length of time.)
	(i) Excessive current in armature	(i) Too much load	(i) Reduce load or increase size of motor.
	(j) Grounds in armature or commutator	(j) Defective insulation	(j) Remove ground if possible or cut out the grounded coil or bridge grounded commutator bar.

TABLE I—Continued
Troubles of Universal Motors

Symptom	Trouble	Cause	Remedy
	(k) Short circuit in armature	(k) Defective insulation	(k) Cut out short circuited coil and bridge the adjacent commutator bars as a temporary expedient.
	(l) Commutator bars short circuited; mica worn or eaten away, causing deep pits between bars	(l) (1) Copper or carbon dust between commutator bars (2) Melted solder from leads between bars (3) Insulation between brush holders and frame broken down. This also causes a ground	(l) (1) Remove foreign matter from between bars. (2) Remove foreign matter from between bars. (3) Repair insulation.
	(m) Reversed armature coils (NOTE: This will never happen unless the armature has been repaired.)	(m) Cross connection to wrong commutator bars	(m) Test polarity with a compass and connect to proper bars. (NOTE: Direct current will have to be used in a polarity test.)
4. Rings of fire follow the brushes around the commutator	(a) Short circuited armature coil	(a) Defective insulation	(a) Cut out short-circuited coil and bridge the adjacent commutator bars.
	(b) Short circuits between commutator bars	(b) Defective mica or solder joining one bar to next	(b) Scrape out defective mica; scrape a gap in the solder between bars.
5. Flashing or excessive arcing from brush to brush	Excessive voltage impressed on motor windings	(a) Voltage too high on line	(a) Reduce voltage if possible.
		(b) Motor operating on higher voltage than is intended	(b) Change motor for one that will operate on the available voltage. On some motors the leads can be changed for different voltages. On others, shifting the end bells will make the change.
6. Singing of brushes	(a) Brush pressure too great	(a) Brushholder springs not properly adjusted	(a) Remove part of the brush tension by compressing the springs.
	(b) Brushes too hard		(b) Replace brushes with ones of softer material. The use of graphite brushes will eliminate singing. (NOTE: A small quantity of vaseline on a clean rag rubbed on the commutator will help to reduce singing. The commutator should be wiped off immediately after doing this.)

TABLE I—Continued
Troubles of Universal Motors

Symptom	Trouble	Cause	Remedy
7. Chattering of brushes	(a) High bars	(a) Cone or V-ring holding commutator segments in place loose	(a) Carefully drive high bars back into place and tighten cone at the end of the commutator. Smooth commutator with sandpaper or true in a lathe. Larger sizes may be trued with a stone.
	(b) Low bars	(b) Rough handling, or wearing away due to soft bars, or from short-circuited coils	(b) Loosen cone and lift bars even with others. It may be necessary to insert a new cone, as the old one may be cut through and will eventually ground the commutator. After repairing, the commutator should be trued in a lathe.
	(c) High mica	(c) Copper wears faster than mica	(c) Undercut mica below surface of bars. Remove all dust before putting back in service.
	(d) Loose bars	(d) Cone or V-ring loose	(d) Tighten cones, test for grounds with a Megger, magneto, or bank of lamps, and true commutator in a lathe or with sandpaper.
	(e) Improper end play	(e) Fiber washer worn on smaller sizes; shaft collars or bearing worn on larger sizes	(e) Replace fiber washer on small sizes; adjust shaft collars, if any, on larger sizes.
	(f) High ridges on commutator	(f) Brushes not staggered over the surface of the commutator. On the smaller sizes, it is impossible to stagger the brushes	(f) Place armature in a lathe and true the commutator.
8. Armature hot all over	(a) Overload	(a) Overload	(a) Reduce load.
	(b) Moisture in coils	(b) Operating in a damp place	(b) Dry out by running at light or no load, or bake in an oven.
	(c) Armature out of center between poles	(c) Bearing worn on one side	(c) Renew bearing.
	(d) Eddy currents in armature core	(d) Faulty construction	(d) No remedy but to rebuild the armature core with thinner laminations.

TABLE I—Continued
Troubles of Universal Motors

Symptom	Trouble	Cause	Remedy
9. Armature issues a pounding sound	Armature striking or rubbing pole pieces	Bearing worn on one side	Renew bearings.
10. Motor fails to start	(a) Load too great	(a) Load too great	(a) Disconnect load to see if motor runs light.
	(b) Friction	(b) Bearing too tight	(b) Polish shaft with emery cloth.
	(c) Fuse blown	(c) Overload or short circuit	(c) Replace fuse and try again.
	(d) Open circuit in line	(d) Wires broken or disconnected	(d) Examine line and connections and repair if this is the trouble. Open up the motor leads and test both line and motor leads. Test motor leads with a Megger or a magneto. Test line with a Megger, magneto, bell and battery, or a lamp.
	(e) Open circuit in field or field connections	(e) Rough handling or original short circuit which may have burned a coil or connection	(e) Examine field connections and test with a Megger, magneto, test lamp, or voltmeter.
	(f) Open circuit in armature	(f) Rough handling or original short circuit which may have burned a coil or connection	(f) Test out adjacent commutator bars and locate the trouble. Bridge the gap as a temporary expedient. Rewind coil or whole armature. (NOTE The motor may show a tendency to run if the brushes span the open-circuited bars.)
	(g) Short circuit in field	(g) Dampness or defective insulation	(g) Bake if damp; rewind if defective insulation. If motor has more than two poles, it may show a tendency to start with direct current; but if there are two poles only, it will not start. If alternating current is impressed on the windings, the insulation will immediately start smoking.
	(h) Brushes not in contact with the commutator	(h) Brushes fit too tightly in holders or holders are loose	(h) Adjust brushes so that they work easily in holders

TABLE I—Continued
Troubles of Universal Motors

Symptom	Trouble	Cause	Remedy
	(i) Poor commutation	(i) Brushes not set on neutral point	(i) Move end bells on some types; move stator core inside frame on other types. The different types are readily indicated by the extra holes in the frame and stator core. (NOTE: This defect will not occur unless the motor has been taken apart for repairs and wrongly assembled.)
11. Motor runs backward	Reversed connection	Reversed connection	(a) Reverse either field or armature connections if operated on direct current. (b) Reverse the direction of the current through either the field or armature on the straight series commutator type if operated on alternating current. (c) Shifting the end bells 90 degrees will reverse some of the compensated types. This shifts the compensating winding in relationship to the brushes. The compensating winding on this type is 90 degrees from the main winding. (d) On some types, especially those used on drills, it is impossible to reverse the direction when using alternating current without reconnecting the stator windings. The direction of rotation on these motors is determined by the polarity of the field windings, that is, the connections are so made that the armature moves from the main winding toward the compensated winding.

Repairing short circuits on four-pole motors

A short circuit of an armature coil will cause the coil to become much hotter than those adjacent to it and is therefore easily located. When located, a short-circuited coil may be cut out and the motor operated without it. Care must be used, since the method of cutting out a coil varies with the type of winding.

Where the armature winding is connected single-parallel (a lap winding), a defective coil is cut out as shown in Fig. 7. First, the coil is cut at the back of the armature, as shown in the diagram. Next, the motor is connected to the line and allowed to run a few revolutions to ascertain which commutator bars the defective coil

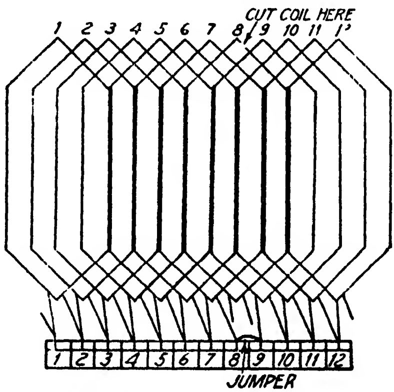


Fig 7 Method of Cutting Out a Defective Coil in a Single-Parallel (Lap) Winding

was connected to. When stopped, it will be noticed, if the proper coil is cut, that the mica between two of the commutator bars is burned, indicating that the coil was connected to the two bars on either side of the burn. The leads from the defective coil are then cut off at the bars and a jumper connected across the two bars, thus completing the circuit through the armature, which should be tested with a lamp circuit or a Megger before putting the motor back into service.

Where the armature winding is connected single-series (a wave winding), owing to the way the leads are connected to the commutator (the winding is two-circuit), the procedure in jumping a defective coil is somewhat different from that in the foregoing.

In this case, the defective or short-circuited coil is cut, as in the case of a single-parallel winding, and the motor connected to the line

to locate the commutator bars to which the short-circuited coil is connected, the same as before; but it will be noticed after stopping the motor that there are two burned spots on the commutator directly opposite each other, as shown in Fig. 8.

If a jumper is connected to bars *4* and *5*, the armature will be open circuited and it is therefore necessary to also connect a jumper from bar *11* to bar *12*. This, however, short circuits coil *2*, which must also be cut out of circuit. In order to jump the defective coil properly and save the good coil, a jumper is connected from bar *5* to bar *11*, as shown at *B*, Fig. 8.

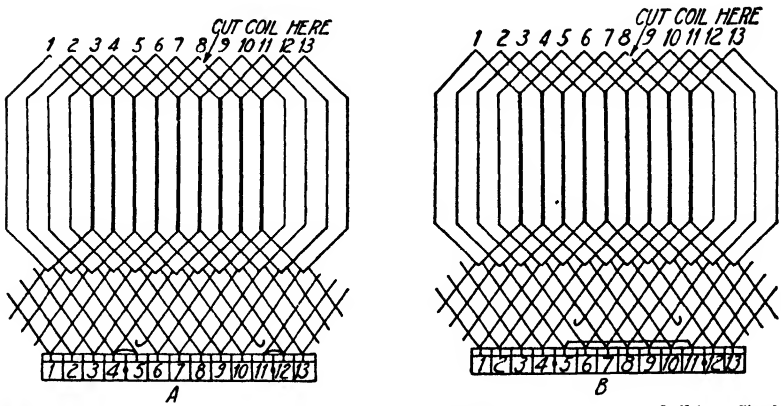


Fig. 8. Wrong Method (A) and Right Method (B) of Cutting Out a Defective Coil in a Single-Series (Wave) Winding

Repairing short circuits on two-pole motors

A short circuit may be between turns, between the top and bottom halves of coils, in the coil leads, or in the commutator. Where the short circuit is between turns, only one coil is affected. To locate, connect a bank of lamps in series with the armature winding and a low voltage supply, and touch adjacent commutator bars with the leads of a low reading voltmeter or millivoltmeter, as shown in Fig. 9. If there is a dead short circuit, the meter will show a zero reading; if only partially short circuited, it will show a partial reading; while all coils not short circuited will give the same or full readings.

Another method, and one which is probably more reliable, is to use a growler. A growler is a coil wound over a horseshoe-shaped

laminated core, the ends of the horseshoe being opened about the ordinary width of an armature slot. Low voltage alternating current is impressed on this coil, which is in principle the same as the primary of a transformer. Any coil in the armature over which the growler is placed then acts as a secondary for the transformer. After placing the growler over a given slot, a feeler is placed over the slot in which the other side of the coil is located. If this feeler vibrates, the coil under it is short circuited.

To repair, open up the leads at the commutator and tape them back out of the way, and insert a jumper between the commutator bars thus vacated by the defective coil.

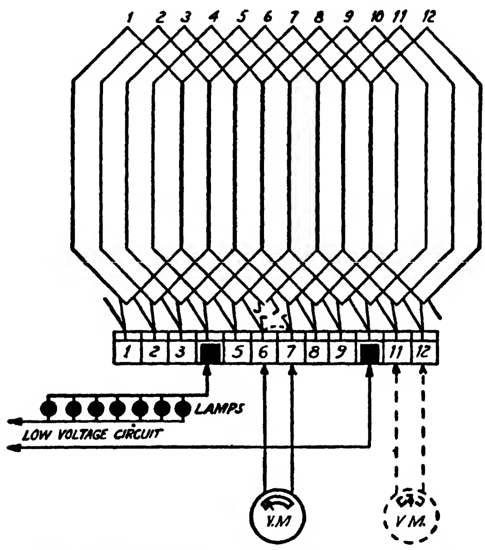


Fig. 9. Method of Locating and Repairing an Open Circuit in a Parallel (Lap) Winding

A short circuit between top and bottom halves can be located by the growler, although in this case there will be a different effect, and the method of repair is different. Since two coils are affected, two coils must be cut out of circuit. The same procedure is used in making repairs, that is, the ends of the two coils are taped back and two jumpers inserted. With two dead coils in the armature the remaining coils have to divide the voltage; and when the voltage is too great, the remaining coils often burn out, with the result that the armature has to be rewound.

A quick test to ascertain whether the short circuit is in the commutator or in the armature is made with the growler in the following manner. After locating the apparently short-circuited coil or coils, bridge the two commutator bars at the seat of trouble with a screwdriver blade. If when contact is broken at one bar a spark is seen at the point of break, the winding is short circuited. If no spark is seen, the commutator is short circuited.

Short circuits between coil leads are harder to locate, and it is sometimes necessary to lift the top leads in order to locate. If the insulating strip between the top and bottom leads does not appear charred and there is no solder between the leads, it may be taken for granted that the trouble is in one of the other locations mentioned above.

Repairing open circuits

Just as the effect of a short circuit varies in series-connected and parallel-connected windings, so does the effect of an open circuit also vary.

An open circuit in a parallel winding is indicated by flashing of the brushes at one spot on the commutator, since the circuit is broken when the brushes pass the break at every revolution. With a parallel winding it is not necessary to test for the location of the open circuit since it is readily apparent. To repair, all that is required is to bridge the gap by connecting a jumper between the two commutator bars between which the arcing occurs. If time will permit, it is safer to remove the leads of the open-circuited coil, since if the circuit is accidentally closed through the ends of the break coming together, the coil will be short circuited and will heat up and may cause considerable damage to adjacent coils. Make sure that the leads so removed belong to the open-circuited coil, otherwise there will be another open circuit. In order to determine that the circuit is complete through the armature, a test lamp in series with a low-voltage circuit is used.

The method of locating and repairing an open circuit in a parallel winding is shown in Fig. 9. The bank of lamps shown in the diagram is connected to a suitable source of low voltage, either direct or alternating (providing the voltmeter is for the same circuit), and to the brushes of the motor which are left in contact with the commutator. With the voltmeter leads connected to segments *11* and *12*,

as shown in the diagram, normal deflection of the voltmeter needle will result. With the voltmeter leads connected to segments *5* and *6*, *7* and *8*, or *8* and *9*, there will be no deflection of the voltmeter needle. With the voltmeter leads connected to segments *6* and *7* or those segments to which the open circuited coil was originally connected, current will flow from the brush on segment *4*, through coils *4*, *5*, and *6*, thence through the meter and through the coils connected to segments *7*, *8*, *9*, and *10* to the brush on segment *10*. The resistance of the meter being many times greater than the resistance of the armature windings, practically full voltage between the brushes will be indicated by the meter.

If the open circuit does not occur in the leads from the windings to the commutator and it cannot be located, the assumption is that the break is somewhere in the slots and the two leads should be cut and taped so that there is no possibility of their coming together and a jumper connected as shown by the dotted line between bars *6* and *7*.

When an open circuit occurs in a series winding, one-half of the coils are dead. Unlike a parallel winding, an open circuit in a series winding is indicated by a burned spot between commutator segments for every pair of poles—that is, for a 4-pole winding there are two burned spots; for a 6-pole winding there are three; etc.

In testing for an open circuit in a series winding, the apparatus required and the diagram of connections both for the test and the method of repairing are shown in Fig. 10.

The same equipment is used for this test as is used for the parallel winding, only the results of the test are different. With supply voltage on the brushes and the voltmeter leads connected to bars *5* and *6*, the meter will be violently deflected, since all the voltage in one-half the winding is impressed on the meter. The same effect is obtained if the meter leads are connected to bars *11* and *12*.

In repairing an open circuit in a series winding, one jumper only is required. This differs from the procedure of repairing a short circuit in a series winding, as with a short circuit, two jumpers are required. The jumper is connected to the bars each side of the break, as shown in Fig. 10. If jumpers are connected at each point where arcing occurs, heating will occur in the two coils adjacent to the break. These coils are not short circuited but are connected in parallel, and since the voltage is too high for them, a circulating

current flows between them. Since these coils not only carry their share of the armature current but also this circulating current, they will heat up; and if the motor is fully loaded, they will burn out.

Great care is therefore necessary in diagnosing the cause of trouble in series winding, to determine if the fault is due to a short circuit or an open circuit.

A better method of inserting the jumper is that which is outlined in connection with a short-circuited coil in a series winding. Cut the coil completely out so that there is no possible chance of it short

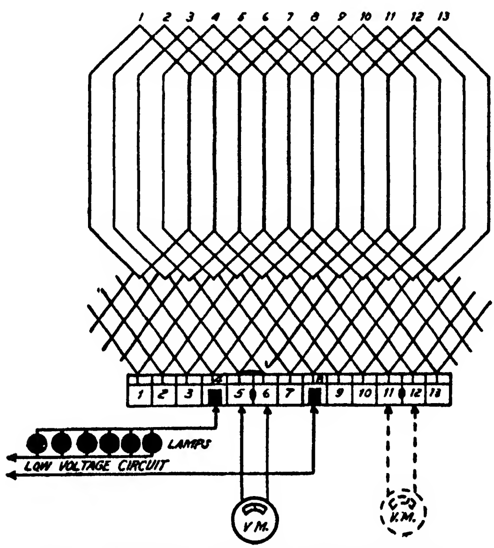


Fig. 10. Method of Repairing an Open Circuit in a Series (Wave) Winding

circuiting accidentally and connect the commutator bars adjacent to the break by means of a long jumper, as shown in Fig. 8 at *B*.

Repairing a commutator

A great many temporary repairs can be made to a commutator, which if made with care also constitute permanent repairs. Among those repairs mentioned in Table I, the most common is the cutting of ridges formed on the surface of the commutator by the wear caused by the brushes. The quickest method of reducing these ridges is by the use of a commutator stone. So simple is the use of the stone that the motor need not be taken out of service. The only precaution is

that the brushes should be worked up and down in the holders to keep the carbon and copper dust caused by the action of the stone from fouling. This operation should be performed every half minute.

A short circuit in a commutator causes excess heating of the segments each side of the defect, and it is usually determined by the darkened appearance of these segments or bars. A short circuit between two bars of a commutator also has the effect of cutting the coil connected to these bars out of the armature circuit by short circuiting the coil and, unless immediately repaired, will burn out the coil so short circuited.

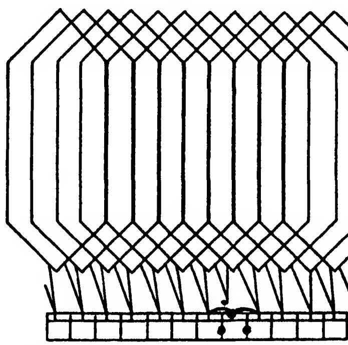


Fig. 11 Method of Repairing a Short Circuit between Adjacent Commutator Bars

It is necessary to be absolutely certain that the trouble is in the commutator and not in the winding, and in order to locate the exact point of trouble, the following test should be made.

If a voltmeter is convenient, a suitable voltage and current are applied to the motor brushes which are left in contact with the commutator. Touching the voltmeter leads to successive commutator bars will show by the voltmeter readings the seat of the trouble. When the voltmeter leads are connected to bars which are not shorted, the normal voltage across the coil registers. When connected to short-circuited bars, the reading is lower, depending on the resistance of the short circuit. If the short circuit is due to carbon or copper dust in a cavity in the mica, a reading of from zero to one-half normal voltage is shown; while if there is a dead short circuit, there will be no deflection of the meter needle.

While this test will locate the exact location of the short circuit, it does not indicate whether the defect is in the commutator or in the coil, and it is therefore necessary to disconnect the leads from the commutator and again test as before. The diagram of connections for this test is shown in Figs. 9 and 10.

There are three methods of repairing a short circuit in a commutator which will put the motor back in service without much loss of time and, except on very small motors, does not necessitate the removal of the armature.

(1) Dig the mica if burned between adjacent bars until the mica appears a gray or normal color and fill the cavity thus made with a mixture of powdered mica, orange shellac, and plaster of Paris. This hardens and dries quickly, after which the motor may be put back into service.

If the trouble has been due to a repair job and there is no burned cavity between the bars and the voltmeter shows no deflection, the cause may be due to solder spanning the two affected bars. If this is the cause, the solder may be removed with a sharp knife. If the cause is due to the bars being knocked together copper to copper, a file can be used to cut the copper to the mica and thus correct the fault.

(2) If the nature of the defect is deeper than the above causes, as would be caused from grounding of two bars, the ends of the coil which is short circuited by the defect are lifted from the commutator and taped apart. This procedure cuts out a good coil but puts the motor in shape for operation.

(3) Lift the ends of the two coils which are connected together at the commutator bar on one side of the defective spot (it makes no difference which side) and connect these together back of the commutator, as shown in Fig. 11.

Repairing faults due to grounds

A ground in an armature may be caused from various reasons and may be either in the winding or in the commutator or in both. When a ground occurs in both the winding and the commutator on rare occasions, the result is usually a short circuit, since, while not impossible, it is highly improbable that two grounds may occur in the same section, that is, in a coil and in the commutator bar to which one side of the coil connects.

A ground in a coil is usually caused from stresses or poor insulation. If the slots are poorly insulated and the coils not packed tightly in them, stresses due to centrifugal force and magnetic induction may chafe the insulation and allow the conductors to come in contact with the core.

Another cause may be due to insulation failure at the end of the slot, the coil not being brought out straight enough before making

the turn around the back of the armature. A ground in the winding may also be due to rough usage in removing the armature from the frame.

A ground in the commutator may be due to rough usage, a short circuit, an open circuit, loose clamping rings, and other causes. The cones which clamp the commutator to the shaft are insulated from the commutator with sheets of mica and, if the clamping ring becomes loose, the mica is liable to shift and allow the segments to come in contact with the cones.

Another cause of a ground in a commutator may be due to a path formed between a segment and the clamping ring due to high voltage, oil and dirt, or failure of the insulation back of the ring. This fault will not happen unless the frame of the motor is grounded, but since all motor frames must be grounded, the fault can happen from the causes enumerated above.

In order to locate a ground in either a coil or a commutator bar, the winding must be divided into open sections by removing the leads from the commutator. Each section is then tested by means of a lamp in series with a low-voltage circuit, one end of the test set being permanently connected to the shaft while the other end is successively touched to the various sections of the commutator.

When the faulty or grounded section is found, the leads of all coils in this section are disconnected from the commutator and each coil and segment tested separately. After the ground is located, if in a coil, the coil is either removed or cut out of circuit.

When testing for a ground with a voltmeter, the grounded segment or coil will give a smaller reading than a normal segment or coil.

Repairing field windings

The faults that may happen to the field windings of a universal motor are open circuits, short circuits, and grounds.

An open circuit in a field winding may be caused by the connections becoming loose through vibration or rough handling. Since the field and armature are connected in series, a break in the field winding or connections will make the motor inoperative.

In order to locate the break, the armature is disconnected from the field and each tested separately. If the break is in the connections, it is a simple matter to repair; but if the break is in any of the

field coils, the motor must be taken out of service and a new field coil inserted.

A short-circuited field coil may be caused by the leads coming in contact with one another; by the insulation breaking down between two turns in different parts of the coil; by moisture in the coils; and by grounds.

The leads coming in contact with one another will completely short circuit the field coil. This seldom happens unless the leads are soaked in oil and heated up by an overload on the motor so that the insulation is charred and broken off.

The insulation breaking down between two turns in different parts of the coil only partially short circuits the coil, the amount of the field winding short circuited depending on the location of the turns which are together. This defect may be caused by turns of highly different potential crossing one another accidentally at the outside end turns.

The moisture in the coil is caused from the motor operating in a damp location and the coils not being properly impregnated against moisture.

Grounds may be caused from moisture breaking down the insulation on one field or on two fields, the first being a local short, the latter a short circuit of sections of two coils; and if the motor has two poles, both fields are short circuited and practically all the current flows through the armature.

A short-circuited field coil, if motor is operated on direct current, is indicated by its being cooler than the rest of the coils; but as this is not always reliable, a better method of testing is in the use of a voltmeter by which the drop of potential is measured across each coil. Where none of the coils are short circuited, the voltmeter reading across each coil is equal to the line voltage divided by the number of coils in series. If one coil is short circuited, the voltage drop across this coil is less than that across the others (anywhere from near full reading to zero). With a zero reading, the coil is completely short circuited, and thus puts all of the voltage on the remaining coils, which is the cause of their being hotter than the defective coil. On alternating-current motors, a short-circuited field coil is hotter than the others and is easily located.

A VIEW OF THE METHOD USED IN WINDING THE STATOR OF A 100 HORSE-POWER, 1200 R P M , 440 VOLT FYNN WEICHSEL MOTOR

Courtesy of Wagner Electric Corp

REPULSION-INDUCTION MOTORS

Introduction. Owing to the difference in design and characteristics, single-phase motors of the following types cannot be classified in general as to methods of keeping them in running condition and repairs, and it is therefore necessary to treat each type separately.

The repulsion start induction motor manufactured by the Century Electric Company, the compensated induction motor manufactured by the Wagner Electric Corporation, and the repulsion induction motor manufactured by the General Electric Company and Wagner Electric Corporation are representative types of single-phase motors.

CENTURY REPULSION-INDUCTION MOTOR

Operating instructions*

In order to keep a Century repulsion-start-induction motor in perfect running order and cut the cost of maintenance, the following points should be observed.

(1) Keep the bearings well oiled.

(2) Keep the commutator clean.

(3) See that the brushes are of proper length and that they press at all points on the commutator.

(4) See that the brushes move freely in the holders. An accumulation of dirt and oil will prevent them from functioning properly.

(5) See that the starting load is not too great. A Century motor will carry a much greater load after it is running at full speed than it will bring up to speed, since it has a greater torque at running.

(6) See that the governor functions properly. After the governor has functioned and the motor is up to full speed and carrying load, the spring barrel ring should enter the bore of the brush-holder rigging sufficiently to allow the parallel motion fingers which are fastened to the brush holder to rest on the outside of the ring. In its proper position, the governor should allow a clearance of at least $\frac{1}{8}$ inch between the commutator and the brushes. The governor mechanism should be oiled sparingly, just enough to keep it from rusting and not enough to allow an accumulation of dirt which will clog it. The governor mechanism should also be blown out occasionally.

*The author is indebted to the Century Electric Company for information supplied on operating instructions.

(7) See that the spring barrel does not stick in the brush holders when the motor is at rest. If this is allowed, the brushes cannot come to their normal position against the commutator. If the brushes are not in contact with the commutator in starting, the motor cannot start.

(8) Be sure the connections are properly made for the voltage of the line. If the connections are made for 220 volts and the line voltage is 110 volts, the governor cannot function properly if the motor is starting under load, since it cannot develop sufficient torque to accelerate properly.

(9) See that the short-circuiting device functions properly. If the segments do not make contact with the commutator bars, the brushes will arc after the governor has functioned. The short-circuiting brushes should be cleaned occasionally.

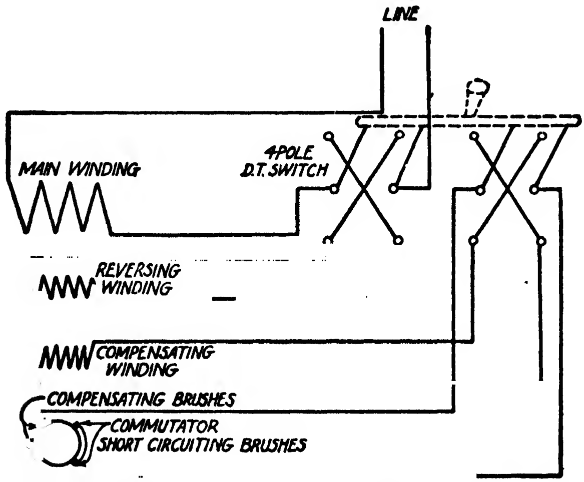
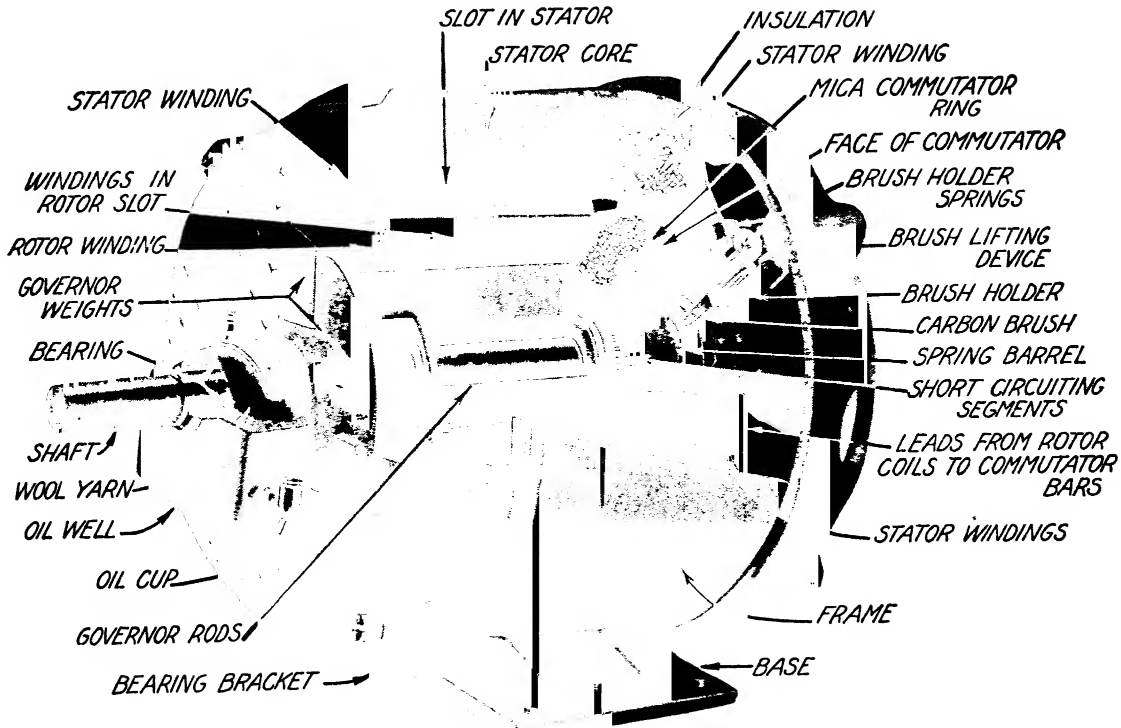


Fig. 1. Diagram of Connections for Reversing a Single-Phase Century Motor

Reversing direction of rotation

The direction of rotation on a Century motor is changed by shifting the brush holder. On the commutator end of the motor there is a brass plate attached to the end bracket with two lines marked on it. At these marks are the letters "R" and "L", indicating right-hand and left-hand rotation. To reverse the motor, loosen the set screw and move the brush holder to the opposite letter.

Where it is desired to reverse the direction of rotation without shifting the brushes, the motor is wound for this duty and four extra leads are brought out from the winding, which connect to a reversing double-throw switch, Fig. 1. Before reversing the motor, it is necessary for the governor to return to the normal starting position.



INSIDE VIEW OF A CENTURY REPULSION-START SINGLE-PHASE INDUCTION MOTOR

TABLE I

Troubles of Century Motor

Symptom	Trouble	Cause	Remedy
1. Hot bearings	(a) Bearing dry	(a) Not sufficient oil, oil rings not working	(a) Refill with clean oil, after washing bearing with kerosene.
	(b) Bearing dirty	(b) Dust or dirt in oil	(b) Refill with clean oil, after washing bearing with kerosene.
	(c) Bearing tight	(c) Not sufficient oil, oil rings not working, or particles of metal sheared off and deposited at other parts	(c) Scrape bearing and shaft or replace bearing. (NOTE Never use ice or water on a hot bearing unless the motor is kept running as it is liable to spring the shaft.)
	(d) Oil rings not working	(d) Rings out of slots	(d) Replace rings, making sure no metal adheres to sides of slots. If rings stick or run slowly, bevel at either top or bottom with a fine file.
	(e) Bearing binding	(e) Shaft out of true	(e) Place shaft in a lathe and true and renew bearing.
	(f) Bearing out of true	(f) Too much strain on pulley	(f) Bearing should be shimmed with thin pieces of tin as a temporary expedient, or replaced by a new one.
	(g) Loose bearing	(g) Vibration	(g) Tighten set screws holding bearing in journal.
2. Brushes do not leave commutator when motor is nearly up to speed	Governor fails to function	(a) Low voltage	(a) See that connections are made for proper voltage. Test voltage with a lamp to determine its value.
		(b) Overload	(b) Remove load to see if governor functions with motor running light. If it does, remove part of the load.
		(c) Governor sticking	(c) If the motor is operating in a cold location, the oil on the governor may stick and make its action sluggish. Wipe off excess oil or apply kerosene sparingly.

TABLE I—Continued

Troubles of Century Motor

Symptom	Trouble	Cause	Remedy
		(d) Frequency of circuit different from that for which motor is designed	(d) If a 60-cycle motor is operating on a 25-cycle circuit, its speed is only $\frac{25}{60}$ of what it was on 60 cycle, therefore the governor cannot function. Replace the motor with one of proper frequency.
		(e) Governor out of adjustment	(e) Remove load and determine if motor will come up to speed and operate the governor. If the governor does not function, the fault may be due to too great a tension on the spring barrel. If the speed of the motor decreases after the governor has functioned, loosen the spring barrel nut, which is situated on the armature shaft at the commutator end, one or more turns.
3. Speed of motor fluctuates	Governor cuts in and out frequently	(a) Governor tension not correct for frequency of the circuit	(a) Adjust the tension, first, by slacking off on the spring nut, and then tightening tension until the desired setting is obtained.
		(b) Variation of circuit frequency	(b) No remedy. The frequency usually settles down after a few moments.
		(c) Change of circuit voltage	(c) No remedy. The voltage usually settles down after a few moments.
		(d) Low voltage due to motor wiring not being heavy enough for intermittent overloads	(d) Increase size of wires supplying motor.
		(e) Loose connection at motor terminals or in the circuit	(e) Locate and repair.
		(f) Overload	(f) Remove part of the load or increase size of motor.
		(g) Poor contact between short-circuiting segments and commutator	(g) Remove any accumulation of oil and dirt and sandpaper the segments.

TABLE I—Continued

Troubles of Century Motor

Symptom	Trouble	Cause	Remedy
4. Abnormal arcing at the brushes	(a) Short circuit in armature circuit	(a) (1) Carbon between commutator bars	(a) (1) Remove with a three-cornered file.
		(2) Insulation burned from leads connecting to commutator	(2) Tape the leads if at all possible.
		(3) Complete short circuit of one or more armature coils	(3) These may be jumped, but it is better to remove and replace them. (NOTE: To test for a short circuit in the armature: (1) Remove all load from the motor. (2) Raise brushes from commutator. (3) Connect the motor to the line. (4) Turn the armature by hand.) If a short circuit exists in the armature windings, the armature will stick opposite each pair of poles. The short-circuited section will be indicated by the armature jumping while the defective section is passing the center of a pole.
	(b) Loose contact between short-circuiting segments and commutator	(b) Segments jammed in holders	(b) Sandpaper the segments and commutator and see that short-circuiting segments are not sticking.
5. One section of the stator winding hotter than the others	Short-circuited field winding	Defective insulation, or leads short circuited	The only practical remedy for a short-circuited field winding is to rewind it.
6. Motor heats up although the load is no greater than ordinary	Displaced air gap	Bearings worn	There should be a clearance of from .015″ to .030″ between the armature and field. The only remedy is a new bearing.
7. Motor fails to start	(a) Load too great	(a) Load too great	(a) Disconnect load to see if motor starts light.
	(b) Friction	(b) Bearings too tight	(b) Scrape bearing and see if it turns easily on the shaft.
	(c) Fuse blown	(c) Overload or short circuit	(c) Replace fuse and try again.

TABLE I—Continued

Troubles of Century Motor

Symptom	Trouble	Cause	Remedy
	(d) Open circuit in line	(d) Wires broken or disconnected	(d) Examine line and connections; test with a magneto to locate break and repair.
	(e) Open circuit in stator	(e) Rough usage or original short circuit which may have burned a coil or connection	(e) Open up the various connections on the stator coils, test each one until the open-circuited coil is located, then rewind it as a coil in a stator winding of this kind cannot be jumped.
	(f) Rotor rubbing the stator core	(f) Bearing worn	(f) Replace bearing, or shim the bearing if possible. To shim a bearing place a thin sheet of tin under it.
	(g) Open circuit in armature	(g) Rough handling or original short circuit which may have burned a coil or connection	(g) Test out adjacent commutator bars and locate the trouble. Bridge the gap as a temporary expedient. Rewind coil or whole armature.
	(h) Brushes not in contact with the commutator	(h) (1) Brushes too short (2) Brushes stuck in holders	(h) (1) Renew brushes. They should all be exactly the same length. (2) Work brushes back and forth in the holders to loosen them.
	(i) Poor commutation	(i) Brushes on neutral	(i) Shift the brushes to the side of neutral that gives the proper direction of rotation.

There are four leads brought outside the frame of the Century motor so that the two halves of the winding can be connected in series for 220 volts, or in parallel for 110 volts. Fig. 2 shows the manner in which to connect the motor for different voltages.

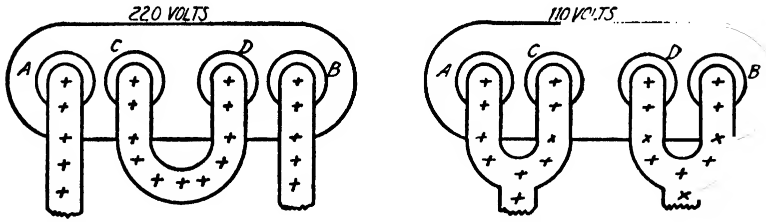


Fig 2 Method of Connecting the Leads of a Century Motor to Operate on Different Voltages

Locating troubles

Owing to the construction of a Century motor, the troubles encountered may be as much mechanical as electrical. The usual troubles encountered are found in Table 1.

WAGNER ELECTRIC MOTORS

Wagner motors are made in both compensated winding and repulsion induction types. Of the older types, the "BK" is an example of the compensated induction motor, while the "8W5BA" is an example of the repulsion induction motor. Their latest types which have superseded both the older types of compensated and repulsion induction are the "66" and the "76XRA". Since there are several of the older types to be found in operation, a brief description is given of them.

The compensated induction motor is essentially a squirrel-cage rotor induction motor with a compensated winding on the stator in addition to the regular stator winding, and a commuted winding similar to a direct-current winding and a commutator on the rotor in addition to the squirrel-cage winding. The squirrel-cage bars are placed in slots under the direct-current winding and are separated from them by magnetic bridges. The squirrel-cage bars are connected together at each end of the armature by end rings, as in a polyphase induction motor. There are two sets of brushes on the commutator—one set being connected in series with the compensated winding, the

other set short circuited. The commutator is parallel to the shaft. In starting, the brushes connected to the compensated winding are held from the commutator by means of a centrifugal switch, and do not make contact with the commutator until approximately 85 per cent of full speed is attained. When running, both sets of brushes are in contact with the commutator, the compensated winding acting as an auxiliary winding to maintain a high power factor in the motor.

Operating instructions*

In order to keep a Wagner Electric "BK" motor in perfect running order, the following points should be observed:

(1) Keep the motor well oiled.

(2) Keep the commutator clean and slightly undercut.

(3) See that the brushes fit properly on the commutator and are free to move in the holders.

(4) See that the centrifugal switch functions properly and that the brushes connected to the compensated winding are not in contact with the commutator while the motor is being started. If these brushes make contact in starting, a heavy starting current will flow through the winding; and since this winding is of smaller conductor, it is liable to burn out, especially if the motor is loaded.

(5) See that the short-circuiting brushes are in contact with the commutator both in starting and running.

(6) Blow out the windings and brush rigging with a hand bellows or blower as soon as an excess of dirt is noticed.

(7) See that there is proper clearance between the rotor and stator.

Locating troubles

The troubles usually encountered with "BK" motors, together with their symptoms, causes, and remedies are found in Table II.

Type "BA" and "RA" motors

The Wagner "BA" motor is similar to the "RA" type in performance, the main feature of the "RA" being its simplicity of construction. On the "BA" motor, the brush-holder assembly comprises thirty-six parts and the governor mechanism twenty-two parts, while on the "RA" type there are fifteen parts in the brush-holder assembly and six in the governor mechanism.

The stators of both the old and new types have only one winding—of the concentric type. The special characteristics of these motors are secured by the rotor construction. The rotor carries a

*For some of the operating instructions the author is indebted to the Wagner Electric Corporation.

TABLE II

Troubles of Wagner "BK" Motor

Symptom	Trouble	Cause	Remedy
1. Hot Bearing	(a) Bearing dry	(a) Not sufficient oil or oil rings not working	(a) Refill with clean oil, after washing bearing with kerosene.
	(b) Bearing dirty	(b) Dust or dirt in oil	(b) Refill with clean oil, after washing bearing with kerosene.
	(c) Bearing tight	(c) Not sufficient oil, oil rings not working, dust or dirt in oil, or particles of metal sheared off and deposited at other parts	(c) Scrape bearing and shaft or replace bearing. (NOTE Never use ice or water on a hot bearing unless the motor is kept running as it is liable to spring the shaft.)
	(d) Oil rings not working	(d) Rings out of slots	(d) Replace rings, making sure no metal adheres to sides of slots. If rings stick or run slowly, bevel at either top or bottom with a fine file.
	(e) Bearing binding	(e) Shaft out of true	(e) Place shaft in a lathe and true and renew bearing.
	(f) Bearing out of true	(f) Too much strain on pulley	(f) Bearing should be shimmed with thin pieces of tin as a temporary expedient, or replaced by a new one.
	(g) Loose bearing	(g) Vibration	(g) Tighten set screws holding bearing in journal.
2. Brushes on compensated winding do not make contact with commutator when motor is nearly up to speed	(a) Centrifugal switch mechanism fails to function	(a) Overload	(a) Remove load to see if switch functions when the motor is running light. If it does, remove part of the load.
		(b) Low voltage	(b) Test the voltage with a lamp or voltmeter.
		(c) Switch sticks	(c) Oil sparingly and work a few times by hand.
		(d) Wrong frequency	(d) Motor designed for a frequency other than that of the circuit.

TABLE II—Continued
Troubles of Wagner "BK" Motor

Symptom	Trouble	Cause	Remedy
3. Compensated winding heats up	Brushes connected to this winding in contact with the commutator during the starting period	Centrifugal switch does not function	Overhaul switch and oil sparingly and operate it by hand a few times.
4. Abnormal arcing at the brushes	(a) Short circuit in armature circuit	(a) (1) Carbon dust between commutator bars	(a) (1) Undercut commutator with a file or slotter.
		(2) Insulation burned from leads connecting to commutator	(2) Tape leads if at all possible.
		(3) Complete short circuit of one or more armature coils	(3) Connect a jumper across the short-circuited coil or coils or rewind the armature. If a short circuit exists in the armature windings, the armature will stick opposite each pair of poles. The short-circuited section will be indicated by the armature jumping while the defective section is passing the center of a pole.
	(b) Loose contact between short-circuiting brushes and commutator	(b) Brushes too short or sticking in holders	(b) Renew brushes if former; work the brushes until they are loose in the holders if the latter. Sandpaper the commutator and brushes.
5. Motor heats up although the load is no greater than ordinary	Displaced air gap	Bearings worn	There should be a clearance of from .015″ to .030″ between the armature and field. The only remedy is a new bearing.

winding similar to the winding of a direct-current armature which is connected to a commutator, the face of which is at right angles to the shaft. Short-circuited brushes bear on the commutator. The rotor is equipped with a centrifugal device which is adjusted to operate at about 85 per cent of full speed, at which time the brushes are automatically lifted from the commutator and the commutator is short circuited.

When the motor is at rest, the rotor acts in the same capacity as a direct-current armature with the short-circuited brushes in contact with the commutator. With the stator windings connected to the line, currents are induced in the rotor winding, these currents flowing through the short-circuited brush connections. The brush axis is displaced slightly from the axis of the stator winding, thus producing a high starting torque.

When the motor has accelerated under this torque to about 85 per cent of full speed, the centrifugal governor lifts the brushes from the commutator and short circuits the rotor, thus giving the rotor squirrel-cage characteristics.

Thus, during the starting period, there are two distinct principles of operation. In the initial period, the entire torque results from repulsion motor action; and in the second period of starting, the torque is from induction motor action. By the combination of these two principles of operation there is secured:

(1) A high torque characteristic of repulsion motor starting with a low starting current.

(2) By changing to induction motor characteristics, the speed is maintained constant.

(3) By removing the brushes from the commutator, wear of both brushes and commutator is limited to the starting period only.

Reversing direction of rotation

All types of Wagner repulsion and compensated induction motors are reversed by shifting the position of the brush holders so as to bring the axis of the brushes on the opposite side of the axis of the stator winding. A set screw on the collar fitted to the brush rigging at the commutator end of the motor is loosened in shifting the position of the brushes. After changing the direction of rotation, this set screw should be firmly tightened, otherwise the brushes may shift and interfere with the starting of the motor.

Operating instructions

The instructions for keeping the various types of Wagner repulsion induction motors in proper running condition are the same as for the "BK" compensated induction motor.

Locating troubles

The troubles usually encountered with Wagner repulsion induction motors are the same as for the compensated motor, with the exception of one symptom—the brushes do not leave the commutator when approximately full speed is attained. The trouble is that the governor fails to function because of low voltage; overload; governor sticking; frequency of circuit different from that for which motor is designed; or governor out of adjustment. The following remedies may be applied:

(1) See that connections are made for proper voltage. Test voltage with a lamp to determine its value.

(2) Remove load to see if governor functions with motor running light. If it does, remove part of the load.

(3) If the motor is operating in a cold location, the oil on the governor may stick and make its action sluggish. Wipe off excess oil or apply kerosene sparingly.

(4) If a 60-cycle motor is operating on a 25-cycle circuit, its speed is $\frac{25}{60}$ of its former speed and, therefore the governor cannot function. The only remedy is to replace the motor with one of proper frequency.

(5) Remove load and determine if motor will come up to speed and operate the governor. If the governor does not function, the fault may be due to too great a tension on the spring barrel. If the speed of the motor decreases after the governor has functioned, loosen the spring barrel nut which is situated on the armature shaft at the commutator end one or more turns.

GENERAL ELECTRIC MOTORS

The General Electric "RI" and "RSA" single-phase motors differ from the Wagner repulsion motors in that the brushes are in contact with the commutator both in starting and running. The commutator is parallel to the shaft in both types.

Reversing direction of rotation

The direction of rotation on both the "RI" and "RSA" types is accomplished by shifting the axis of the brushes to the opposite side of the axis of the stator winding. The type "RI" is reversed by loosening the set screw on the brush-rigging collar and shifting the

brushes to the opposite side of neutral. Care must be exercised that the set screw fits in the dowels, otherwise there will be poor commutation and flashing at the brushes, and the motor will run at reduced speed.

The type "RSA" is reversed by shifting the end bells of the motor with respect to the stator windings. There are two sets of holes through the stator core through which the bolts fastening the end bells pass. The brush rigging is permanently fastened to the front end bell so that it is necessary to remove the end bells and slip the bolts through the opposite holes in the stator core.

BALDOR REPULSION-INDUCTION MOTORS

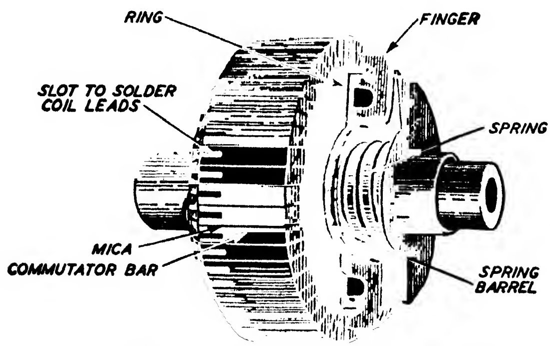
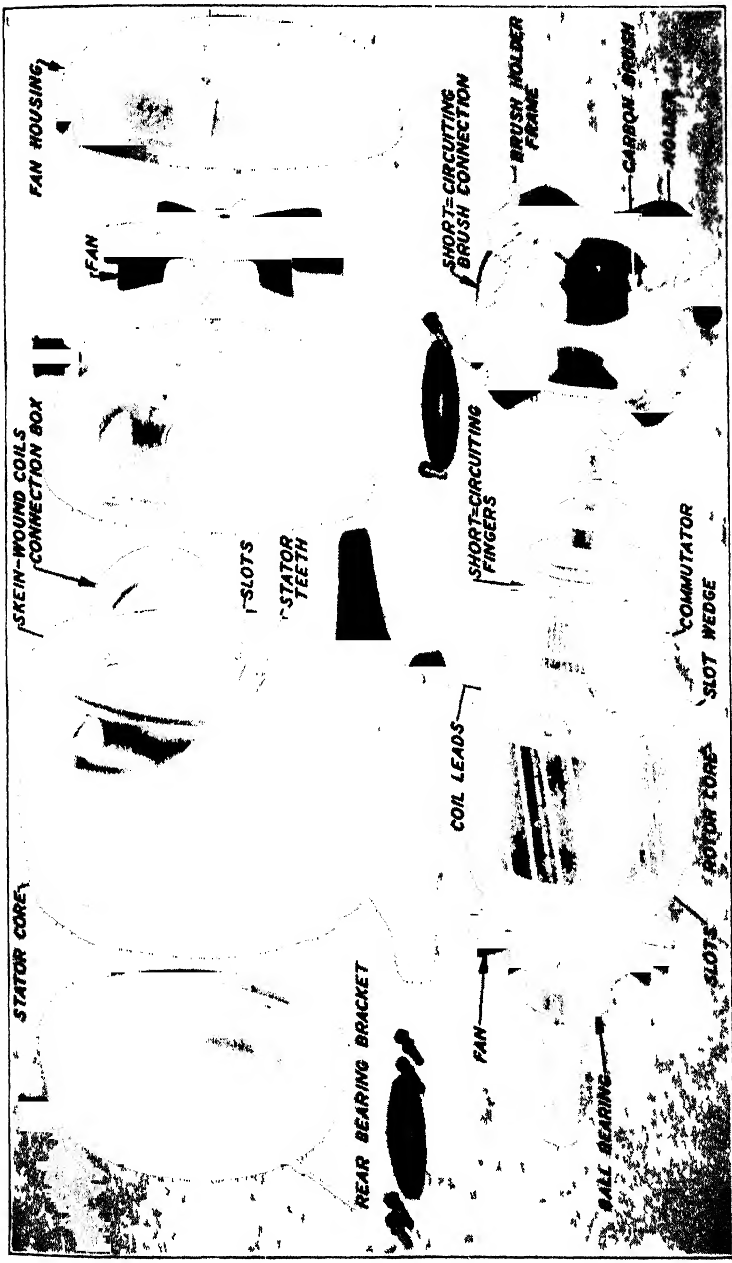


Fig. 3. Cut-away View of Short-Circuiting Switch of a Baldor Motor

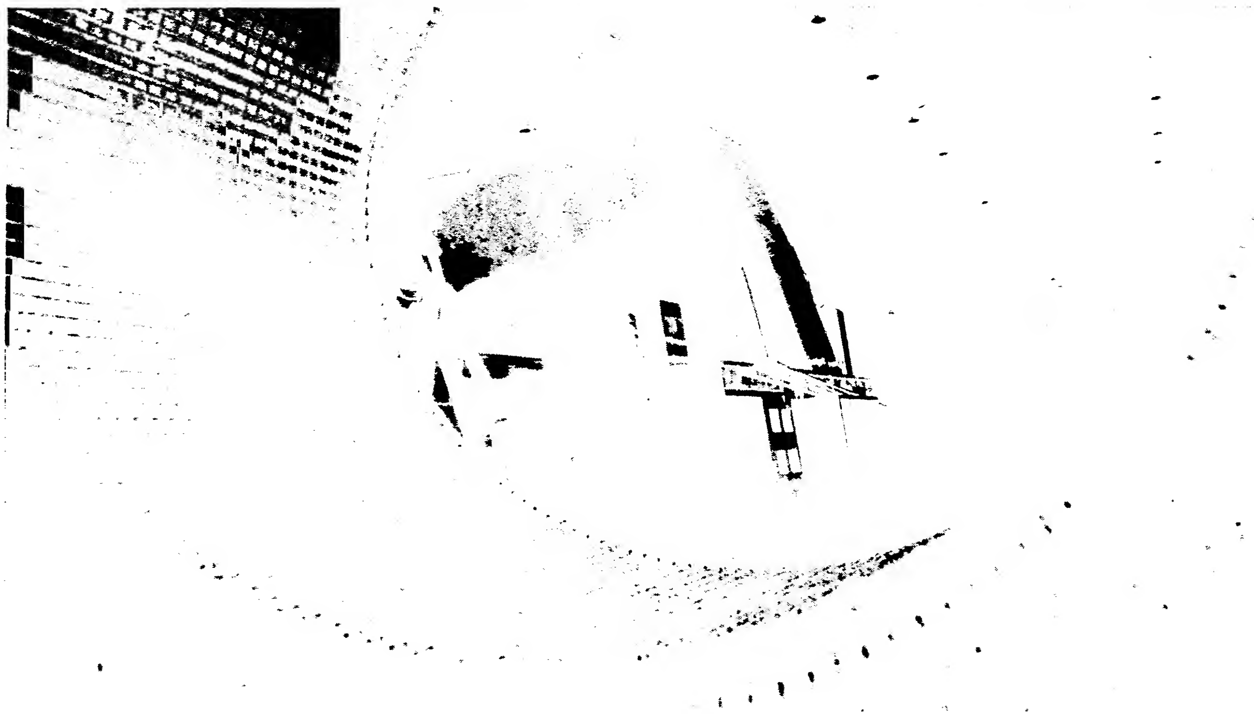
Courtesy of Baldor Electric Co., St. Louis, Missouri

In the Baldor motor the short-circuiting device consists of a large number of fingers, loosely assembled and retained in a housing by a spring, Fig. 3, that pushes against the spring barrel. When the rotor of the motor reaches three fourths of normal speed, the centrifugal force on the fingers is great enough to push the spring barrel to the right and allow the tips of the fingers to touch the ends of the commutator bars. These fingers connect all the bars to the ring, thus short-circuiting all the commutator bars and rotor winding. The centrifugal force holds the fingers in this position until the motor is shut down or an overload stalls the rotor.



UNASSEMBLED VIEW OF A FULLY INCLOSED BALDOR SINGLE-PHASE REPULSION-STARTING INDUCTION-RUNNING BALL-BEARING MOTOR

Courtesy of Baldor Electric Company, St Louis, Missouri



THIS 40,000-HP MOTOR BEING ASSEMBLED IS TO FURNISH POWER FOR DRIVING THE FAN THAT WILL FORCE AIR AT 400 MILES PER HOUR THROUGH THE WIND TUNNEL TO TEST AIRPLANES AT THE NEW WRIGHT FIELD

Courtesy of Westinghouse Electric and Manufacturing Company East Pittsburgh Pennsylvania

POLYPHASE INDUCTION MOTORS

Operating instructions

In order to get maximum operating results from induction motors and their auxiliary equipment, it is necessary to keep the equipment and motor as clean as possible. Dirt of various descriptions is prevalent in every manufacturing plant and constant vigilance is required to combat it.

One of the worst effects of dust and dirt in connection with an induction motor is that it chokes the air ducts in the laminations, fills up the air gaps between the stator and rotor, and contaminates the oil in the bearings. In order to take care of the dust that accumulates in and around the motor windings, either vacuum cleaners or blowers may be used. Suction or vacuum cleaners may be used to good advantage where the dust is of a dry nature, but where the dirt is moisture laden, oil soaked, or adhesive, it is necessary to use compressed air. Caution is required in the use of compressed air, since it always contains moisture; and pressures over one hundred pounds per square inch should not be used, since the windings are likely to be damaged.

The induction motor is of rugged construction and can be built to withstand considerable moisture, fumes of various kinds, and chemicals in powdered or liquid form by impregnating the windings with special varnish under vacuum. While this treatment adds slightly to the cost, it is warranted if the motor is to be subjected to moisture or other foreign substance. If the location of the motor is such that it is subject to overflow of tanks, it may be protected by a metal hood, as shown in Fig. 1. This hood is made from 12 to 14 gauge steel, supported by feet fastened to the frame by the end-bell bolts. If the location of the motor is such that it is subjected to intense heat or severe gases, a metal housing such as is illustrated in Fig. 2 may be used. The housing is provided with an air inlet and outlet from outside the building, through which a current of fresh air passes constantly to the windings. Sliding doors are placed at each end to facilitate oiling and inspection of the motor.

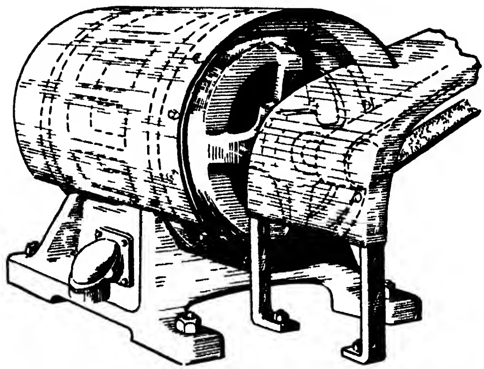


Fig 1 One Method of Housing a Motor to Protect It from Water

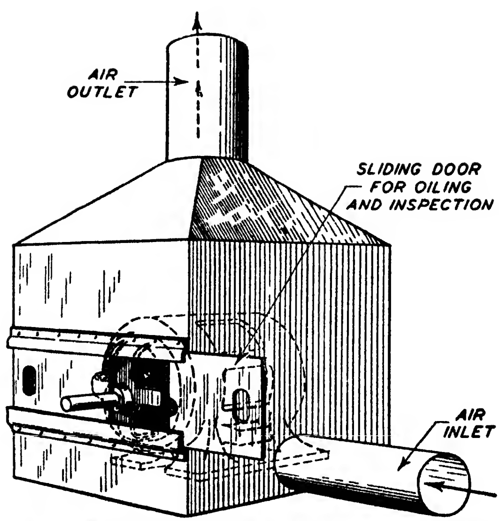


Fig 2. Method of Housing a Motor to Protect It Against Moisture, Fumes, and Dust

The bearings of motors require constant attention if the life of the bearings is to be prolonged. Sleeve or friction bearings cause the greatest amount of trouble of any type of bearing and require almost constant attention. Ball and roller bearings do not require near the attention and, although more costly than sleeve bearings, soon pay for the extra cost in increased life and freedom from repairs and replacements. While it is customary to service sleeve bearings once

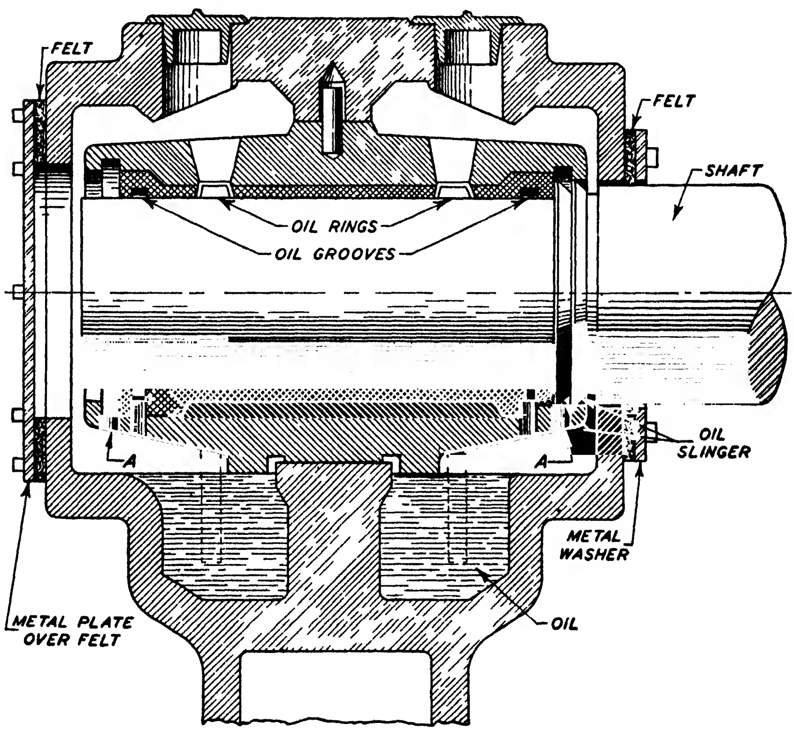


Fig 3 Proper Method of Making a Bearing to Prevent the Oil from Siphoning

daily, ball and roller bearings require servicing approximately once every three months for high-speed bearings and once every six months for low-speed bearings.

Sleeve bearings which are not properly fitted allow the oil to siphon out where it is drawn onto the windings. One way of preventing this from happening is to equip the bearing as shown in Fig. 3. Holes are placed in both ends of the bushing to allow the oil to drop

through into the oil chamber, and the ends of the bearing are fitted with felt washers which prevent siphoning.

Oil softens the insulation and soaks into the windings, and when the windings are subjected to heat as from an overload, the insulation becomes brittle, cracks, and allows any foreign matter to come in contact with the conductors.

Care must be exercised when lubricating a bearing that the overflow pipe or indicator is not clogged. Always examine the oil rings to see if they are revolving.

Care and maintenance

The inspection of motors, or in fact, of any electrical equipment often shows some defect which can be remedied without shutting down the equipment, or at most, for a short time only. Inspections may be divided into daily, weekly, monthly, tri-yearly, and yearly. Table I is given as a guide for properly maintaining electrical equipment. It is not always possible to take every motor in an industrial plant out of service once a year, but it is possible to take some, for instance those having intermittent and periodic duty. It is also possible to dry out a motor that has been immersed or water-soaked by placing space heaters around the frame and covering the whole with a metal hood. At the same time the motor may be treated to a fresh coat of varnish by simply removing the end bells.

Winding defects

The following faults and remedies are intended to show the cause and cure of troubles resulting from wrong connections in a motor which has been totally rewound, partly rewound, or reconnected in any way. It is usual to test a motor in the shop before it is assigned to duty. Winding defects may be classified under the following headings.

(1) Grounds
(2) Short circuit within a coil
(3) Short circuit of a complete coil
(4) Short-circuited pole-phase group
(5) Open circuit
(6) Reversed coil
(7) Reversed pole-phase group
(8) Reversed phase
(9) Wrong grouping
(10) Wrong connection for a given voltage
(11) Wrong speed and number of poles

TABLE I
Care and Maintenance of Induction Motors

Time of Inspection	Bearings	Motor frame	Motor windings	Rotor	Starter	Switches and fuses
Daily	Oil if necessary. See that rings are working. Feel for rise in temperature	Examine ground wire	Feel for excess heating	See if there is proper end play	If in a damp place, feel the oil tank. If hot, it denotes the presence of water in the oil	
Weekly	Examine oil and renew if gritty or darker in color than usual	Adjust end bells to center the rotor if air gap is not the same width at all points	Blow out windings with compressed air or hand bellows, if motor is in a dusty place	Use feeler between rotor and stator to find if rotor is out of center	Overhaul starter if motor is started and stopped frequently	Inspect and clean if necessary
Monthly	Renew oil on all high-speed motors and all others situated in dusty locations				Overhaul starters	Inspect and clean
Tri-yearly	Bearings should be drained and cleaned with kerosene and the oil renewed. High-speed sleeve bearings should be carefully examined and in most cases renewed. Ball bearings should be cleaned and greased		If windings are subjected to corrosive elements, motor should be thoroughly cleaned and baked, windings revarnished and again baked	Rotor should be cleaned and if wound rotor, it should be treated same as stator		
Yearly	Renew all bearings that are badly worn	Frame should be cleaned with kerosene and painted	All windings should be cleaned, varnished and baked	Rotor overhauled	Oil should be changed in all starters	Switch and fuse contacts should be renewed if badly pitted

Grounds. Grounds are usually caused in a new winding or in a repaired winding by careless handling or insertion of coils in the slots. If the slot insulation does not extend past the face of the slot, the insulation of the coil is easily damaged if the coil is bent. Again, if the slot insulation extends too far beyond the slot, bending the coil will rip the fiber and a ground may be the result. After inserting each coil in a slot, it should be tested for ground, using either a magneto, Megger, or a bank of lamps. (A Megger should be used if at all possible.) If a ground is indicated, the coil should be taken out or reinsulated before proceeding with the taping. After all coils are inserted and taped, it sometimes happens that a coil which previously tested O.K. is grounded. It is therefore best to test each coil separately before connecting, as the grounded coil is more easily located. If, however, a motor which tested O.K. becomes grounded after being connected, due to rough handling, it may be necessary to use the "smoke method" to discover the ground. This method consists of impressing a higher voltage than normal on the windings. The connection between the windings and frame at the ground will become hot or will arc, and the ground is usually found without much trouble. If, however, it cannot be located by this means, passing a heavy current through the windings may locate it. Care must be exercised in using this method, as the heavy current may injure the balance of the windings. On an ungrounded system and where no other equipment is grounded, a single ground on a motor will cause no damage; but on a grounded neutral system, a ground on a star-connected motor will cause an unbalance in the phase currents, with attendant heating. A ground has little or no effect on a delta-connected motor on a grounded neutral system unless another motor in close proximity to it is also grounded.

Fig. 4 shows a ground in each of two phases, which, while not constituting a dead short circuit, will cause the windings in these two phases to heat up and burn out, since these windings have been shortened. Fig. 5 shows graphically the effect on the windings.

Short circuit within a coil. This is generally due to two layers getting crossed and wedged when the coil is tamped in the slot, as is generally necessary with a basket type coil. A coil thus affected becomes hot if used with normal voltage even if there is no load on the motor. This is the only symptom. A defect of this kind can be

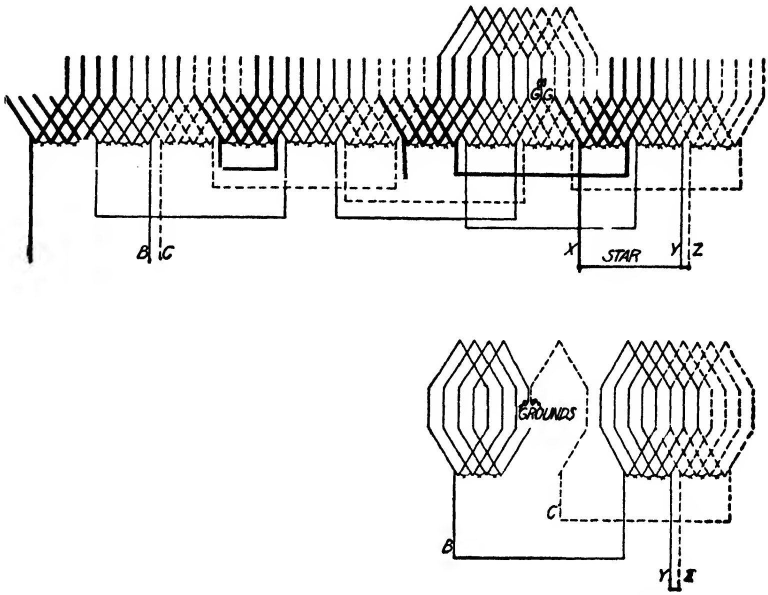


Fig. 4. Showing the Effect of Two Grounds in Separate Phases

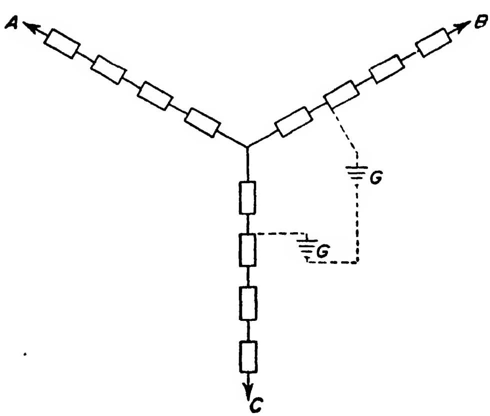


Fig. 5. Graphical Method of Showing the Effect of a Ground in Each of Two Phases

located by means of an exploring coil, Fig. 6. The exploring coil consists of several turns of magnet wire wound around a core of several layers of sheet iron or steel formed as shown in the diagram and open at the bottom. The coil is excited by a low alternating voltage and really constitutes the primary of a transformer, the secondary of which is any coil in the winding to be tested, and over which the primary is placed. The short-circuited coil will be readily noticed by a heavier current flowing in it and by the increased heating. A sure method is to place a small piece of soft iron over the side of the coil opposite to that over which the exploring coil is placed, and if the coil is short circuited, the iron feeler will vibrate

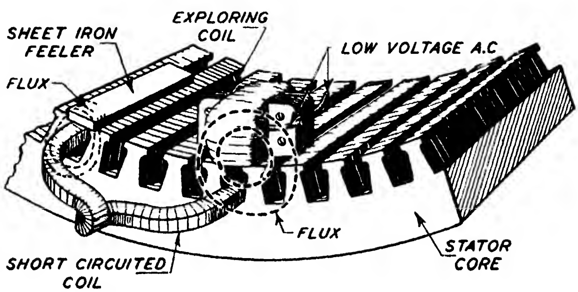


Fig 6 Method of Using an Exploring Coil to Locate a Short Circuit in an Induction Motor

due to the flux produced in the short-circuited coil. The same method is used where a whole coil is short circuited at its stubs or connectors.

Short circuit of a complete coil. A whole coil is short circuited by having its two ends wrongly connected together or to a group connection. The only symptom is that the coil is hotter than those next to it.

Short-circuited pole-phase group. About the only way in which a whole group can be short circuited is by closing the group when making the phase end connections. A defect of this kind is indicated by the group becoming hotter than the remaining groups when voltage is applied to the windings. This defect can be found by means of the exploring coil, Fig. 6; but it is more readily found by the compass method. In order to use the compass test, the stator must be excited with direct current. The use of direct current gives

each pole a set polarity, while with alternating current the poles are continually changing.

When the windings are excited, the compass is moved around inside the stator core and as each pole is approached, the polarity is indicated by the compass. If the north-seeking end of the compass needle is attracted, it will denote a south pole, and vice versa. If the motor has six poles, there will be three north and three south poles in rotation of north, south, north, south, north, south, or vice versa.

In testing two-phase motors, each phase is tested separately and the polarity of each pole marked. When all the poles of each phase have been marked, it will be found that there are two north

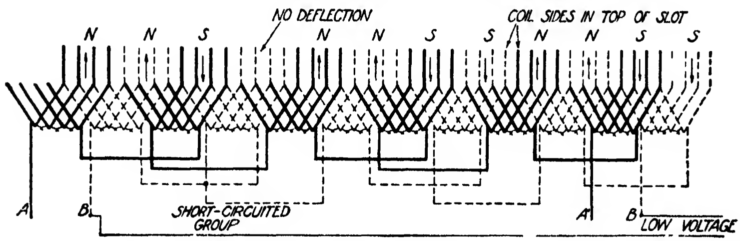


Fig 7. Two-Phase Winding with One Whole Group in Phase *B* Short Circuited

poles together and two south poles together, around the complete winding. If, however, one group is short circuited, there will be no deflection of the compass at that point. Fig. 7 illustrates a two-phase six-pole motor with one group in one phase short circuited.

In testing a star-connected three-phase motor, the direct current is impressed on each of the phase leads, and each phase tested separately as in a two-phase winding. A short-circuited group will be indicated by no deflection. Fig. 8 shows a four-pole star-connected winding with one group short circuited. If there are no short-circuited groups and each pole is marked by an arrow to indicate its polarity, the test will show as in Fig. 9. In testing a delta-connected three-phase motor, one of the delta connections is opened as in Fig. 10. The three phases are now connected in series and the poles of all the phases are tested in rotation. For instance, if the motor has four poles, by the time the compass is moved around the complete winding twelve poles will be indicated; if less than twelve poles are indicated, each one less than twelve will indicate a short-circuited group.

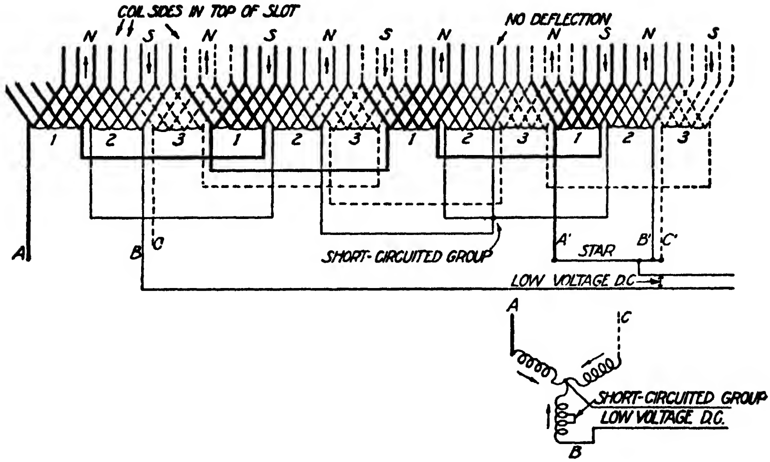


Fig. 8. Three-Phase Star-Connected Winding with One Whole Group in Phase B Short Circuited

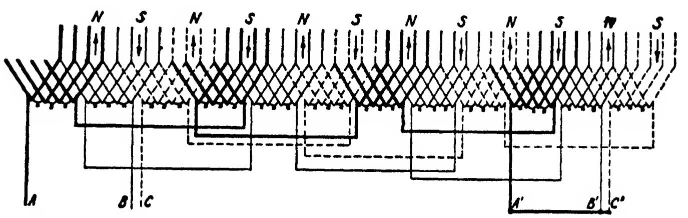


Fig 9 Correct Connection for a 4-Pole Three-Phase Star-Connected Winding

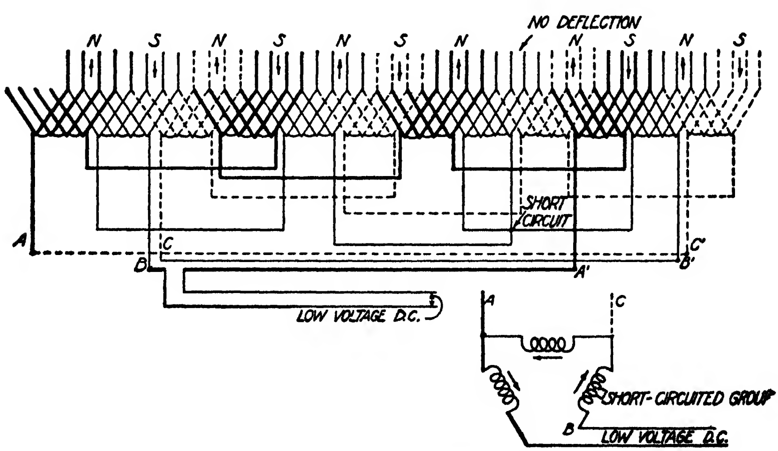


Fig. 10. Three-Phase Delta-Connected Winding with One Group in Phase B Short Circuited

Where direct current is not available, a short-circuited group can be found by means of what is known as the balanced-current test. This is done by means of an ammeter and low-voltage alternating current. In testing out a two-phase motor, the same procedure is followed as with the compass test, as also is a star-connected three-phase motor; while with a delta-connected three-phase motor, each delta is opened, as in Fig. 11, and each phase is tested separately. If no groups are short circuited, the ammeter should give the same reading on each phase, providing the resistance of the windings

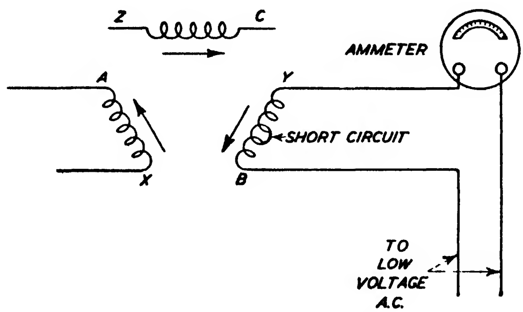


Fig. 11. Balanced Current Test of a Delta-Connected Winding

in each phase is the same. If, however, one group is short circuited, the phase with the short-circuited group will give a higher reading, since the resistance is less.

Open circuit. An open circuit in either a two-phase or three-phase motor with series-connected windings is indicated by the motor standing still and humming; in other words, it acts as if trying to run single phase. It is a simple matter to locate the trouble in a two-phase motor or a star-connected three-phase motor, as a magneto connected to the various phase leads will indicate which phase is open. In connection with a star-connected motor, the magneto should be successively connected to the motor or phase leads and the star in order to locate the open phase.

With a delta-connected three-phase motor, however, the current still has a path, even when one phase is open, as is evident from Fig. 12. It is therefore necessary to open each delta until the phase with the open circuit is located.

When the open-circuited phase is located, the following method is used to locate the exact point of the open circuit in either two-phase or three-phase star-connected or delta-connected motors. Starting at any group, which can easily be determined by the taped

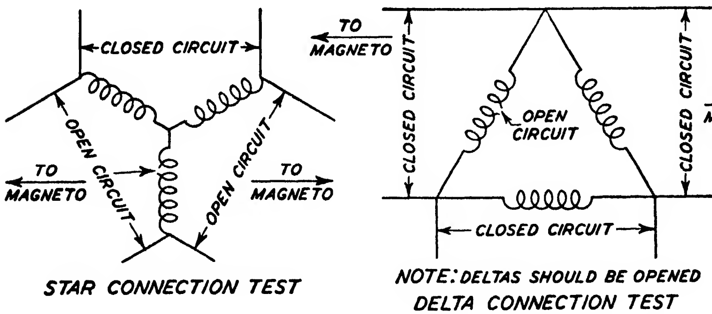


Fig 12 Difference Between Magneto Tests of Star- and Delta-Connected Windings

ends, each group should be marked with chalk, all those of each phase being of the same color and each phase a different color. For instance, in a six-pole three-phase motor there are eighteen groups which may be marked with red, white, and blue chalk around the complete winding, six groups of each color equidistant from each other. After the groups are segregated, a test set such as shown in Fig. 13 is used

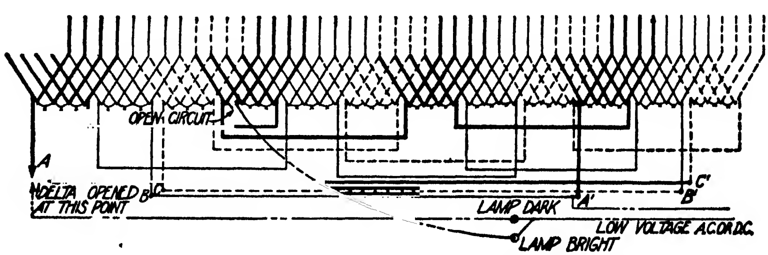


Fig. 13. Diagram for Testing for an Open Circuit in a Delta-Connected Winding by Means of a Lamp Circuit

to locate the open coil or group. One lead or terminal of the set is connected to a motor terminal while the other terminal, which is an ordinary awl, is forced through the insulating tape at the end connections. The test circuit need only be 110 volts, which requires

only one lamp. Starting at the group nearest the phase terminal, each group connection is touched with the awl until one is reached where the lamp does not light. The coil end just touched and the one preceding it in the test are the ends of the open-circuited coil.

Where the windings are paralleled, the symptom is entirely different from that of series windings. The symptom in this case is increased heating in one phase and sometimes in two of the phases. The reason for this is that since the parallel is broken, the remaining winding does not have enough carrying capacity for the load. With paralleled windings it is necessary to open each parallel group and test each separately. This method is shown in Fig. 14.

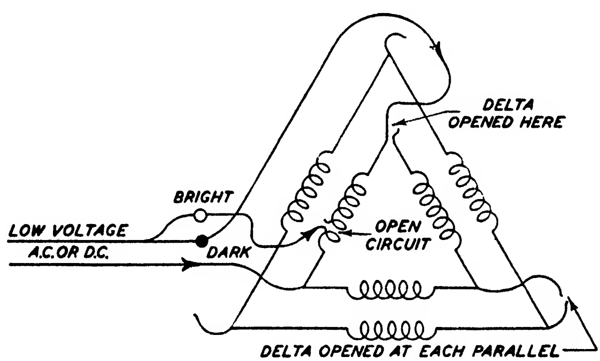


Fig. 14. Method of Testing for an Open Circuit in a Parallel Delta-Connected Winding by Means of a Lamp Circuit

For star-connected motors, the voltmeter method can be used and with either direct or alternating current. A low voltage is impressed on the terminal of the defective phase and the terminal of one of the good phases. A voltmeter is connected to one leg of this circuit and the other terminal is moved along the defective phase (starting at the end of the phase opposite the star) until the seat of the trouble is located. The voltmeter will give a full reading if connection is made at the various end connections until the break is encountered, when there will be no deflection of the needle. This is illustrated in Fig. 15. The trouble is in phase A and the break occurs at O.

Parallel windings may also be tested by the balanced current method to locate an open-circuited coil. The procedure differs between star- and delta-connected motors, however. For star-connected

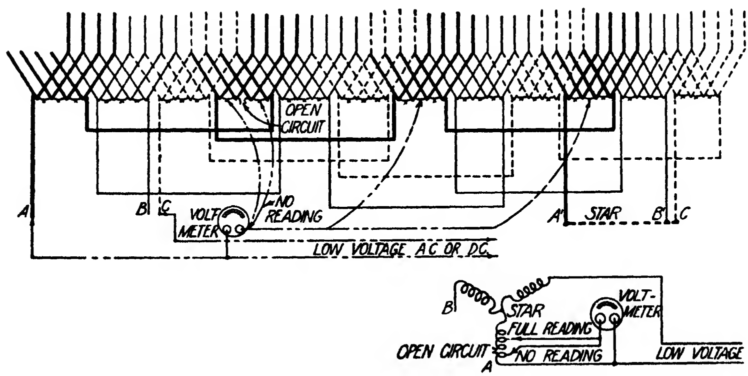


Fig. 15. Diagram Showing Method of Testing for an Open Circuit in a Star-Connected Winding with a Voltmeter

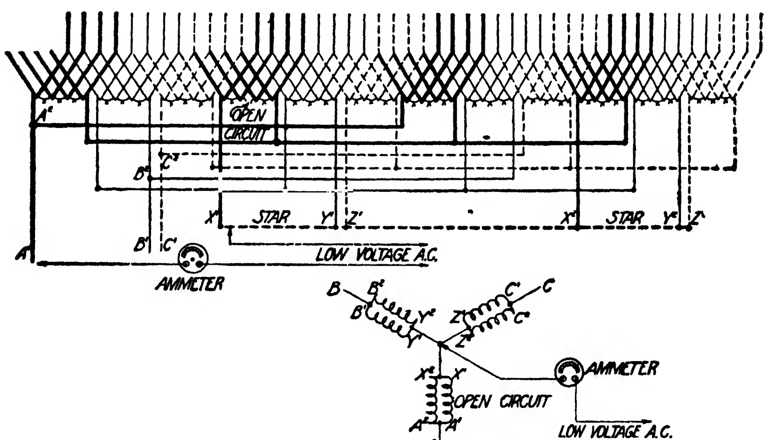


Fig. 16. Balance Test with an Ammeter for an Open Circuit in a Parallel Star-Connected Winding

motors, the star is opened and the current readings taken in each phase. The phase giving the lowest reading will indicate the one with the open circuit. This is illustrated in Fig. 16.

For parallel delta-connected motors, open one delta as in Fig. 12, and test between AB, AC, and BC. In this case, the open circuit is

in one of the parallels of phase A, and the reading between A and B should be lower than between A and C or B and C, as in Fig. 17.

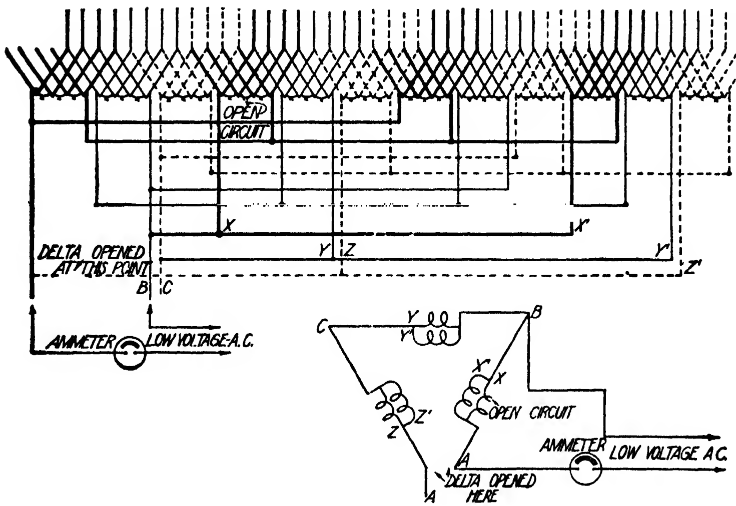


Fig. 17. Balance Test with an Ammeter for an Open Circuit in a Parallel Delta-Connected Winding

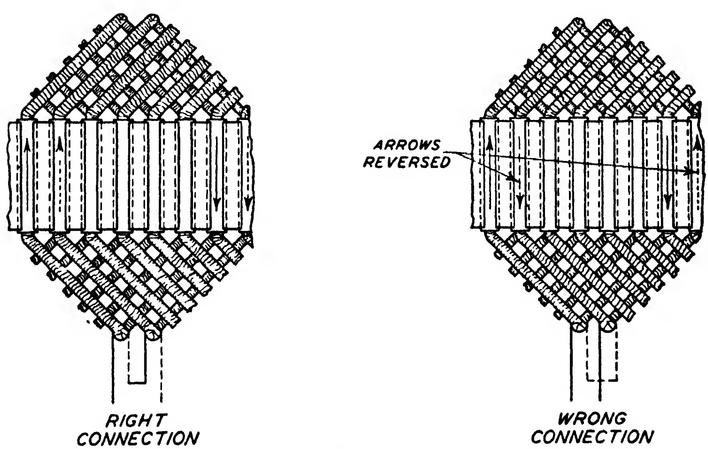


Fig. 18. Correct and Wrong Methods of Connecting Group Coils

Reversed coil. In connecting a group of coils, the bottom of one coil is connected to the top of the one next to it, and so on, as shown in Fig. 18, which illustrates both the correct and wrong method of

connecting. If coil A is connected properly to the balance of the coils and groups of its phase, coil B will be reversed as regards polarity. In locating a fault of this kind, the compass method is used as the balanced-current test would not indicate any irregularity, since the resistance of the phase windings is in no way affected. The test is carried out in the same manner as for short circuits, but the result of the test is different. Instead of getting no deflection of the compass needle, the needle will indicate a reversed polarity when placed over the reversed coil, as shown in Fig. 19. When the reversed coil is located, interchanging the connections of this coil, only, will correct the fault.

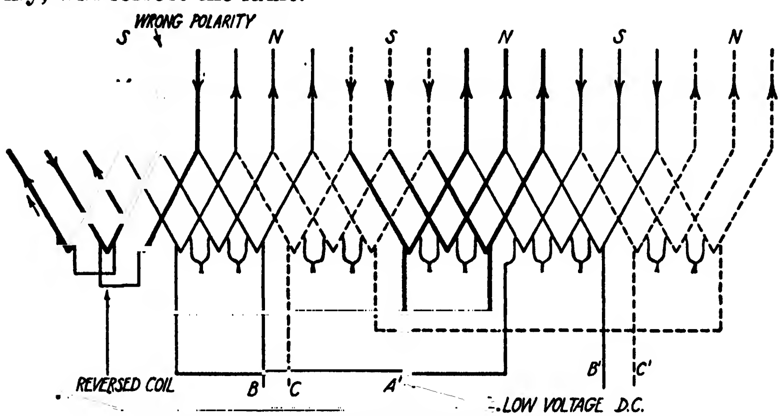


Fig. 19. Showing How a Reversed Coil Affects the Polarity of a Group

The symptom of a reversed coil is that it will heat up greater than the other coils and the motor will issue a peculiar growling noise, since the reversed coil is trying to buck the remainder of the coils in its group—that is, if the other coils in the group have a north polarity, the reversed coil has a south polarity.

Reversed pole-phase group. When a motor is connected adjacent pole, it sometimes happens that in leaving one group for the next, the next group is not crossed, and consequently the polarity of the two groups is the same. Fig. 20 illustrates the correct and wrong methods of connecting adjacent pole. A fault of this kind is located by the use of direct current, in the same manner as in locating short circuits, and a compass test will show three north or three south poles adjacent to one another in either a two or three-phase motor,

as illustrated in Fig. 20. Each group should be checked separately. The symptom of a reversed pole-phase group is similar to a reversed coil, the noise being greater while the heating is slightly less.

Reversed phase. Where one whole phase is reversed, the fault shows up by the unusual behavior of the motor. The speed is affected, that is, reduced to almost nothing if the motor starts at all, which it sometimes does not. The motor emits a harsh groaning sound and the temperature of the windings increases rapidly. The effect is practically the same as if voltage is applied to the stator

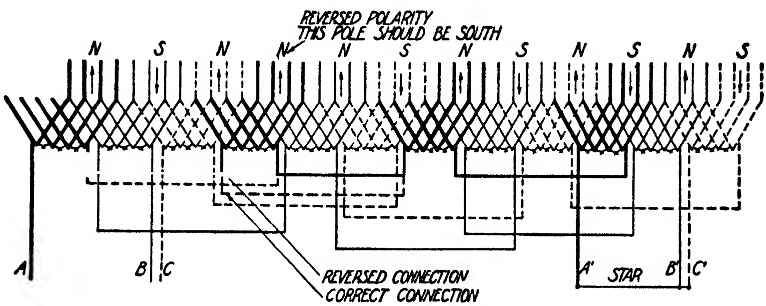


Fig. 20. Diagram of Wrong and Correct Connections Showing the Effect When a Pole-Phase Group Is Reversed

with the rotor removed. The motor cannot develop a counter electromotive force and consequently the current is only limited by the resistance of the windings.

Three-phase motors, only, are affected in this manner, since if one phase of a two-phase motor is reversed, the direction of rotation is also reversed and the motor acts in a normal manner. If one phase of a three-phase motor is reversed, either star or delta, the reversed phase bucks the remaining two. Normally connected, the phases are 120 degrees apart, while with one phase reversed, the reversed phase is opposed 60 degrees only from the other two. The reason for this is that the counter electromotive force in the reversed phase is 60 degrees from the other two phases. In order to correct the fault in a star-connected motor, the reversed phase is opened at the star, the end of the phase winding originally connected to the star is made one of the motor leads, while the original lead or terminal of this phase is connected to the star, as illustrated in Figs. 21 and 22. Fig. 21 also shows the vector relations where one phase is reversed.

Fig. 21 shows a reversed phase in a delta-connected motor, phase *B* being reversed. Changing or reversing the leads *B* and *Y* of phase *B*, that is, connecting *Y* to *C* and *B* to *X*, will correct the fault. (Note the direction of the arrows).

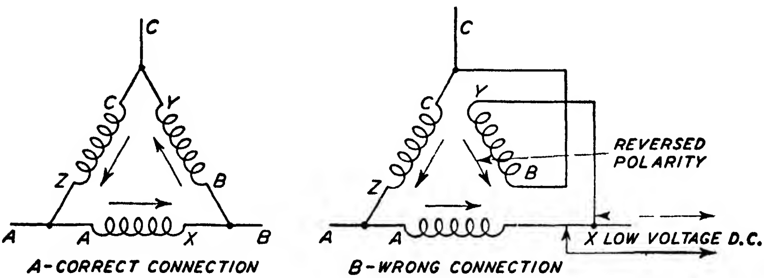


Fig 21 Diagram Showing Connection and Effect of a Reversed Phase in a Delta-Connected Winding To Test, Open the Delta at *X*

Wrong grouping. The number of slots per pole-phase group is found by dividing the total number of slots by the sum of the poles times the number of phases. In connecting a winding, the groups should first be counted and marked. Where a mistake is made, and more coils are connected in one phase than in another, the currents

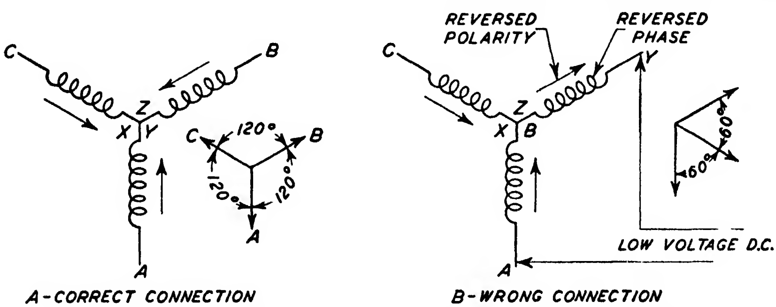


Fig. 22 Diagram Showing Connection and Effect of a Reversed Phase in a Star-Connected Winding To Test, Connect *A* and *Y* to Low Voltage *D C* without Opening the Star Connection

will be unbalanced in all three phases of a three-phase motor, that is, the current in the phase which is correctly connected will be normal, the current in the phase having fewer coils will be higher than normal, while the current in the phase having more coils than normal will be lower than normal. Fig. 24 shows a winding with a

wrong grouping. In this diagram, the correct grouping is four coils, but group three of *A* phase has five coils, while group three of *B* phase has only three coils.

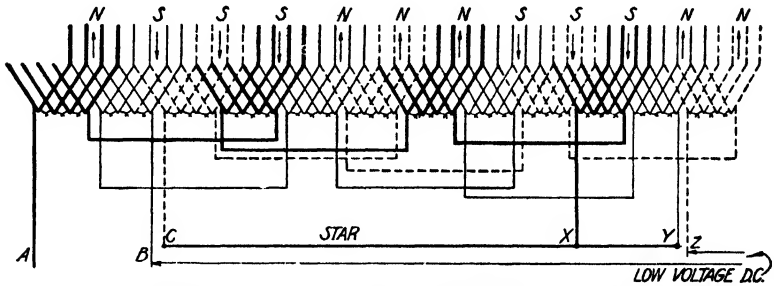


Fig 23 Diagram of Connections for Reversed Phase Note the Effect on the Polarity To Correct the Fault, Connect *Z* to Star and Leave *C* Open

Wrong connection for a given voltage. The effect of wrong voltage impressed on a winding is usually easily detected. If the motor becomes hot and hums excessively when carrying no load, it readily indicates that the voltage is too high for the windings, providing the speed of the motor is normal. In a case of this kind the current is too great for the windings and the magnetizing effect too

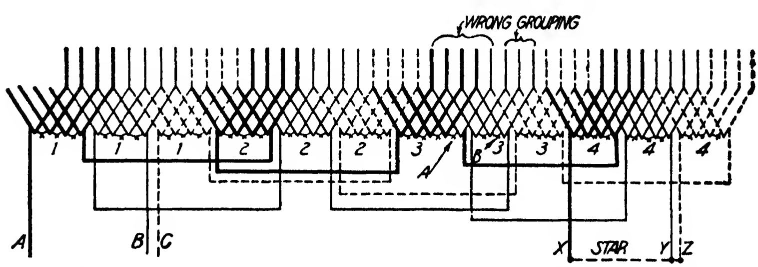


Fig 24 Diagram of Connections for Wrong Grouping Group 3 Phase *A* Has One Coil too Many Group 3 Phase *B* Lacks One Coil

great for the core. If the motor formerly operated at this voltage, the indications point to a wrong connection. If the motor was formerly connected series star or series delta, the conclusion is that the new connection is either parallel star or parallel delta, as the case may be, and the voltage consequently is double what it should be for the connection. Fig. 25 shows a star connection illustrating this fault.

If, however, the original connection was series star and the new connection series delta, the voltage will be 1.73 times too great for the windings. If, on the other hand, the motor apparently runs correctly at no load but loses power and speed when full load is approached, the indication is that the voltage is not high enough; in other words, the torque, which varies as the square of the applied voltage, is not high enough at the motor speed to allow the motor to develop its rated horsepower. A motor formerly connected two-parallel star or two-parallel delta will act in this manner if connected series

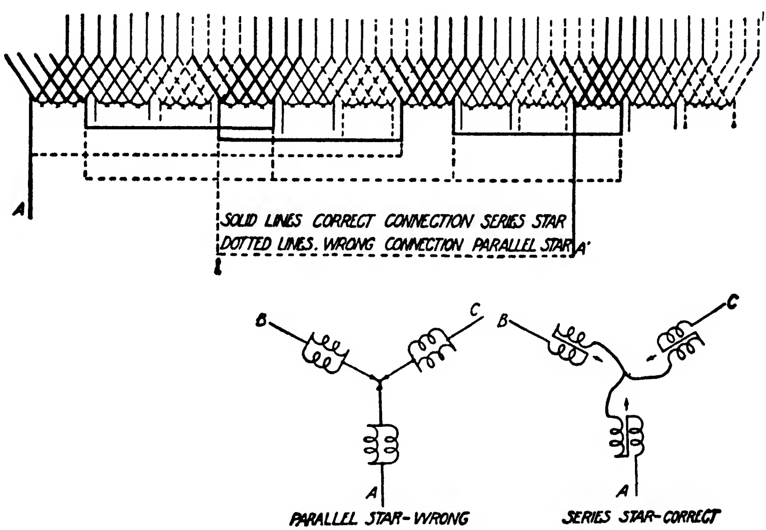


Fig. 25. Diagram Showing Correct and Wrong Connections Affecting the Voltage to the Windings

star or series delta, that is, double the impressed voltage is required for the original output of the motor. Again, if the motor was originally connected series delta or parallel delta and reconnected series star or parallel star, the effect will be the same as decreasing the voltage by 1.73. Fig. 26 illustrates the correct and wrong connections for a case of this kind.

Wrong speed and number of poles. The number of poles equals the alternations per minute divided by the revolutions per minute, and the number of pole-phase groups equals the number of poles times the number of phases. It is seldom that a motor is connected

for a wrong number of poles if the frequency is known, but if such a mistake is made, the only way to locate the fault is to test with a speed indicator. If the speed is wrong and there are no reversed phases, the number of poles will likely be wrong, and the only remedy is to rearrange the pole-phase groups and reconnect the motor.

Operating troubles

The main troubles occurring in the operation of polyphase induction motors are given in tabulated form in Table II, together with the symptom, cause, and remedy. A brief discussion of some of the various items, together with illustrations that might help the operator in readily locating and remedying the fault, follows.

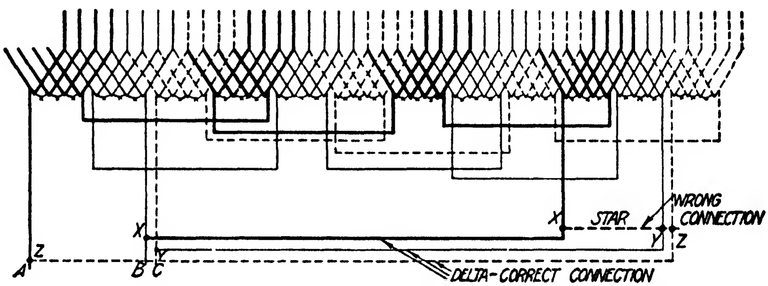


Fig 26 Showing How the Connections Should Be Changed to Change the Effect of the Line Voltage on the Winding

Symptom 1. Bearing troubles need hardly any comment above that given in Table II, but it might be well to state, however, that it is the highest form of economy to use the highest grade of oil for sleeve bearings and the highest grade of grease for roller and ball bearings. Oil is sometimes siphoned from the bearing well, due to the windage of the motor and as a usual thing motor manufacturers guard against this fault. If, however, a bearing is replaced, it should be fitted up as shown in Fig. 3.

Symptom 3. The effect of a displaced air gap is that the flux is not the same in all parts of the motor. Since the reluctance of air is greater than iron, the magnetizing effect will be weakest where the air gap is widest, and strongest where the air gap is narrow. Thus, the iron at this point acts as if overworked, with the result of an increased temperature, which spreads to the windings and soon ruins the motor. This symptom will sometimes lead the operator to be-

TABLE II*

Troubles of Polyphase Induction Motors

Symptom	Trouble	Cause	Remedy
1. Bearing too hot to touch, or smoking	(a) Bearing dry	(a) Not sufficient oil; oil rings not working	(a) Refill with clean oil after first washing the bearing with kerosene.
	(b) Bearing dirty	(b) Grit in oil	(b) Refill with clean oil after first washing the bearing with kerosene.
	(c) Bearing tight	(c) Not sufficient oil; oil rings not working; grit in oil, causing particles of metal to be sheared off and deposited at other parts	(c) Scrape bearing and shaft or replace bearing.
	(d) Oil rings not working	(d) Rings out of slots	(d) Replace rings, making sure no metal adheres to sides of slot. If ring sticks or runs slowly, bevel it at either top or bottom with a fine file.
	(e) Bearing binding	(e) Shaft out of true	(e) Place shaft in a lathe and true and renew bearing.
	(f) Bearing out of true	(f) Too much strain on pulley	(f) Bearing should be shimmed with pieces of tin, as a temporary measure, or replaced with new bearing.
	(g) Loose bearing	(g) Vibration	(g) Tighten set screws holding bearing in housing.
2. Bearing hot, but no hotter than other parts of motor	Heat transferred from rotor or stator of motor	Overload on motor	Decrease load or increase size of motor.
3. Smoke issues from windings; part of windings are hot while remainder are cool; wedges over coils are charred	Displaced air gap or rotor not centered in stator	Bearing worn on one side	If noticed before coils are damaged, realigning the bearing and inserting new wedges will correct the fault; otherwise coils will need to be replaced.

*Courtesy, Electrical World, Oct 29, 1921.

TABLE II—Continued

Troubles of Polyphase Induction Motors

Symptom	Trouble	Cause	Remedy
4. Every second coil in a two-phase motor and every third coil in a three-phase motor are hotter than adjacent coils	(a) Not enough resistance in phase which is hottest, causing unbalanced currents in phases	(a) One or more coils of one phase short-circuited within themselves	(a) Replace short-circuited coil or "jump" the coil** as a temporary expedient.
	(b) One phase grounded	(b) Dampness or damage by foreign material	(b) Remove ground by lifting coil and re-insulating. One ground not serious if motor is not overloaded, when delta-connected. If star-connected, there may be unequal currents between phases. If two phases are grounded, a short circuit is the result.
5. Motor runs hot, and on examination it is found the groups of two phases of a star-connected motor, and the groups of one phase of a delta-connected motor are hotter than other groups	Motor running single phase	One fuse blown or one overload relay out of order	Replace fuse or adjust relay and take ammeter readings of each phase.
6. Motor runs hot and explosions, accompanied sometimes by fire, occur in windings	Temporary ground or short circuit	Due to dampness which causes circulating currents between coils and between any coil and ground	Bake motor until all dampness disappears and dip or brush with insulating varnish. If coils are punctured, replace with new coils. If motor is needed at once, the punctured coils can be cut out, if not too many, as a temporary expedient.**

**Care must be used in "jumping" a coil, and the following points should be observed: Where a phase-boundary coil is cut out or "jumped" care must be taken that no interconnection of phases or wrong groups takes place. In one-layer windings, if the insulation is badly burnt, the coil will have to be completely taken out, since, if only disconnected, circulating currents will be produced which will heat up the "jumped" coil and damage adjacent coils. This is due to there being only one coil side per slot. If more coils than one per phase are burnt. care must be taken that there are enough left to offer enough resistance to keep the current low on account of excess heating.

TABLE II—Continued

Troubles of Polyphase Induction Motors

Symptom	Trouble	Cause	Remedy
7. Motor runs hot with all stator coils the same temperature	Motor usually overloaded	Motor overloaded	Test each phase with an ammeter, and if readings are high, reduce the load or increase the size of the motor.
8. One or more phases hot in spots, while cool in others	Part of windings inoperative	Short circuits between adjacent stator coils	Replace short-circuited coils, as they will usually be found badly charred.
9. Motor refuses to start with starter handle in starting position, although the motor issues a humming sound.†	(a) Motor tries to run single phase	(a) One fuse blown or one overload relay out of order	(a) Replace fuse or adjust relay.
	(b) Air gap displaced‡	(b) Bearing out of true	(b) Shim the bearing or replace with a new one.
	(c) Open circuit in stator windings	(c) Caused either from a short circuit, which might puncture a coil, or from rough handling	(c) Insert new coil or "jump" the damaged one.**
10. Motor starts and runs, but rotor heats up while the stator is cool	Abnormal currents in rotor	Rotor bars loose or grounded	Tighten set screws holding rotor bars to short-circuiting rings and solder or weld them, and remove grounds. In the more up-to-date types of rotors having cast-on end rings, this trouble is seldom encountered.

**Care must be used in "jumping" a coil, and the following points should be observed: Where a phase-boundary coil is cut out or "jumped" care must be taken that no interconnection of phases or wrong groups takes place. In one-layer windings, if the insulation is badly burnt, the coil will have to be completely taken out, since, if only disconnected, circulating currents will be produced which will heat up the "jumped" coil and damage adjacent coils. This is due to there being only one coil side per slot. If more coils than one per phase are burnt, care must be taken that there are enough left to offer enough resistance to keep the current low on account of excess heating.

†Where the rotor is not centered in the stator, it is possible that a motor cannot develop sufficient torque, and consequently will not run, although all fuses are intact. The motor will hum and the rotor will probably turn an inch or so. The symptom is the same as that of a motor trying to run single phase. In a case of this kind insert a feeler between the rotor and stator, and the trouble will show up as an irregular air gap.

‡The following hints will be found useful in locating the trouble: If a motor does not start, (1) examine the fuses; (2) examine the relays; (3) look over the starter carefully; (4) inspect air gap with a feeler; (5) remove belt or coupling, as the case may be, to find if motor is overloaded; (6) test out motor windings with a magneto or bank of lamps. One of these suggestions should locate the trouble, and by applying the proper remedy the difficulty is soon solved.

TABLE II—Continued

Troubles of Polyphase Induction Motors

Symptom	Trouble	Cause	Remedy
11. Motor issues a peculiar sound when running light, as if a heavy load were thrown on periodically with a slight slackening of speed at these intervals	One coil in one phase reversed	Due to wrong connection when being repaired or reconnected	Connect coil to its proper group and in proper polarity.
12. Motor issues a buzzing sound when fully loaded	Loose connection on rotor bars	Overheated bars or rings	Tighten set screws holding rotor bars to short-circuiting rings and solder or weld them, and remove grounds. In the more up-to-date types of rotors having cast-on end rings, this trouble is seldom encountered.
13. Motor loses power and speed when fully loaded	Rotor out of magnetic center in respect to the stator	End play all taken up at one end of shaft due to shifting of bearings; motor out of level; or if direct connected, coupling driven too far on shaft	Level motor; put bearings back where they belong, or move coupling until the rotor will float in the stator.
14. Wound rotor motor runs at half speed	One of the phases open in the rotor windings	One lead to the collector rings broken off or damage to the rotor windings	Test out for the open circuit and repair.

lieve the motor is trying to run single phase, as, if the rotor is almost touching the stator, the motor, if a high speed one, may not start when connected to the line.

Symptom 4. This symptom will show up in both troubles (a) and (b), the effect being practically the same. If the trouble is due to a short circuit in one or more coils of one phase, the winding in that phase is that much less, with the result that a greater current will flow in that phase. The remedy is either to replace the short-circuited coil or coils, which by the way is the only real and lasting remedy, or to jump the damaged coil or coils. When a coil is jumped, it is completely cut out of circuit with the rest of the coils in the group, Fig. 27. Care must be taken that the coil is absolutely open after being cut out, since if it is still short circuited or any part of it closed

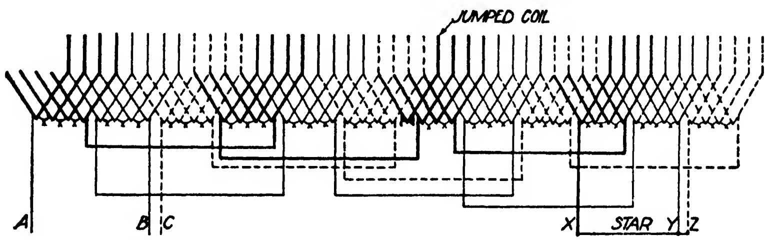


Fig 27 Diagram of Proper Connections Where a Phase Boundary Coil is "Jumped"

circuited, it will immediately heat up when voltage is applied to the windings. The reason for this is that a heavy current is induced in the short-circuited coil by the magnetizing current flowing in the remainder of the motor windings. Unless there are a great many coils per phase, too many coils must not be cut out of any phase, since this increases the voltage per coil in the remaining coils and will cause unbalanced currents in the various phases. Usually not more than one coil per phase should be cut at one time; if more coils are damaged, they should be taken out and replaced with new coils. To locate a short-circuited coil, use an exploring coil, Fig. 6.

Where one phase of a polyphase motor is grounded, there is little or no effect on the motor if the system is ungrounded and no other ground exists on equipment in close proximity to it. On a grounded neutral system there is little or no effect when one phase of a delta-connected motor is grounded and no other motor in close

proximity to it is grounded, since in a delta-connected motor the voltage in any one phase at any instant is exactly equal to and opposite in effect to the other two phases combined. The current in any phase equals the sum of the currents in the other two at any instant, so that no matter in what part of the winding the ground occurs, the unbalance of current will be slight if the motor is not overloaded. Fig. 28 illustrates the paths of the current in a case of this kind. At *A* in Fig. 28, the ground occurs midway in the windings of phase *AB*, while at *B* the ground occurs at the delta *BA*, *BC*. At no time is the voltage in the ground path greater than that in one of the supply phases, which is the star-line voltage.

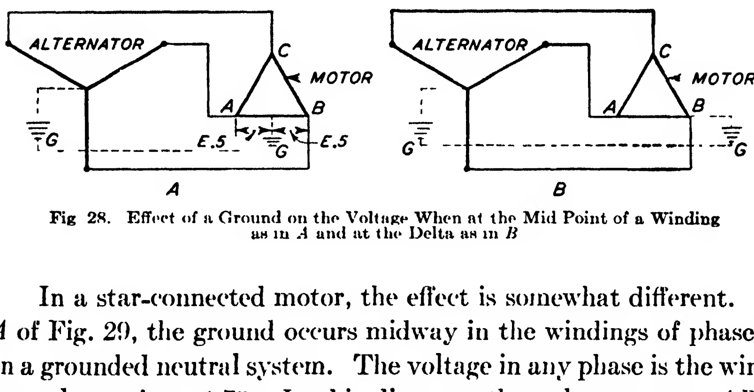


Fig 28. Effect of a Ground on the Voltage When at the Mid Point of a Winding as in *A* and at the Delta as in *B*

In a star-connected motor, the effect is somewhat different. In *A* of Fig. 29, the ground occurs midway in the windings of phase *B* on a grounded neutral system. The voltage in any phase is the winding voltage times 1.73. In this diagram, the voltage across *AB* is *E*1.73. The same applies across *AC*, while the voltage from *B* to ground is *E*.5 volts and from *C* to ground is *E*1.29 volts. At *B* of Fig. 29, the motor is grounded at the star with no evil results and no unbalance. The same applies to *C*, where one of the star terminals is grounded.

If two phases of the same motor are grounded, the result varies as the location of the grounds. If the grounds are the same as in Fig. 4, practically a dead short circuit is the result. If the two phases are grounded as at *A* of Fig. 30, the result is an unbalance in the currents flowing in the different phases. The two affected phases will become exceedingly hot even with no load. If the two grounds occur as in *B*, the effect is not so great; and unless some other motor which has its frame grounded to the same water main is also grounded but in a different phase, the motor will operate quite satisfactorily.

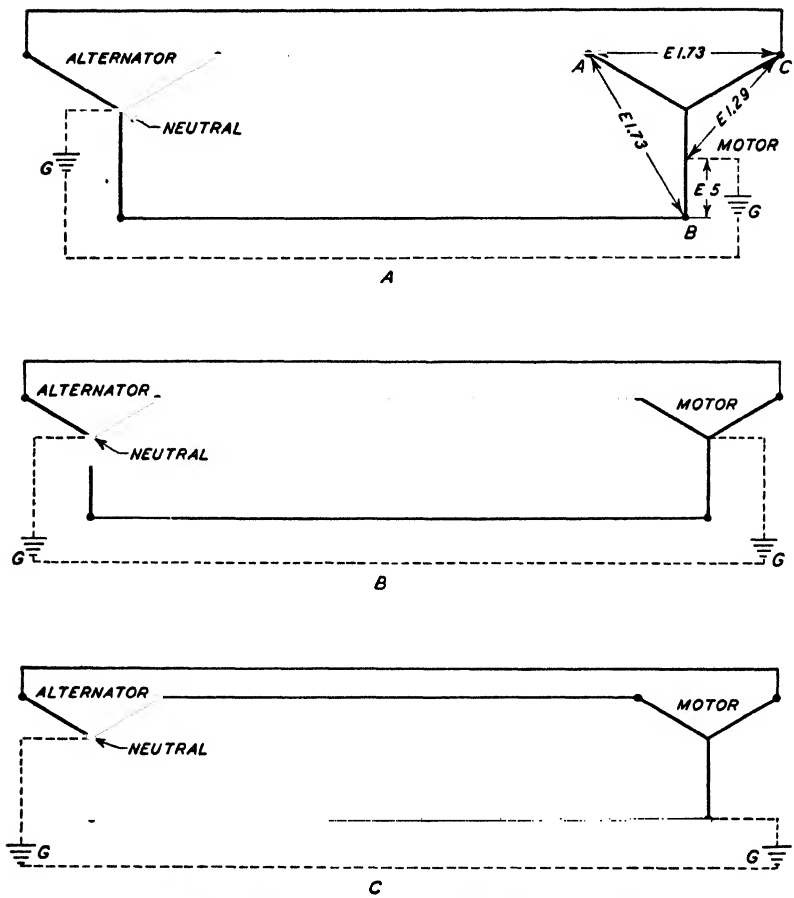


Fig 29 Effect of a Ground on the Voltage at Various Points in a Star-Connected Winding

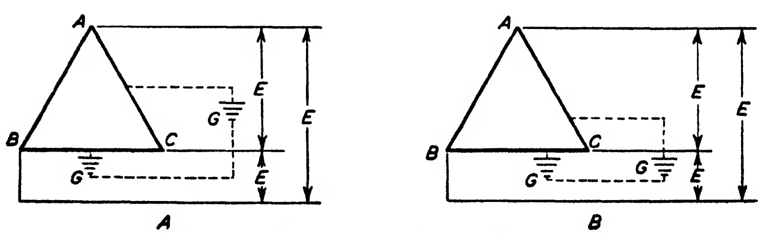


Fig 30 Effect of a Ground on the Different Points of Delta-Connected Winding

Where two delta-connected motors which have their frames grounded to the same water main and a ground occurs in each motor, as shown in Fig. 31, a circulating current will flow through the

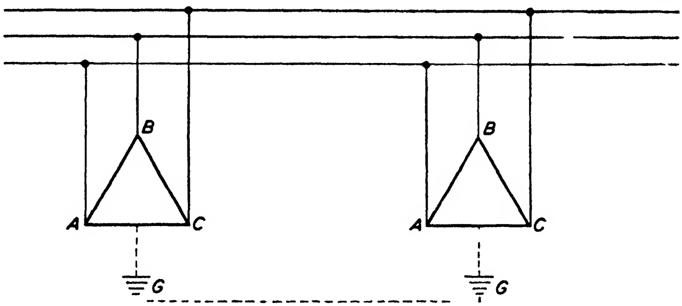


Fig 31 Showing the Path of the Circulating Current between Two Grounded Motors

ground from one motor to the other, the value of the current being determined by the resistance of the ground. Ordinarily a fault of this nature will not interfere with the operation of either motor.

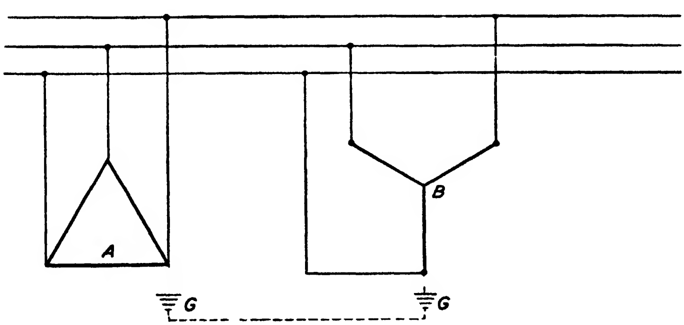


Fig. 32. Effect of a Ground on One Phase of a Delta-Connected Motor and a Ground on a Different Phase of a Star-Connected Motor in Close Proximity to Each Other

Fig. 32 shows the effect of a ground on one phase of a delta-connected motor and a ground on a different phase of a star-connected motor. Both grounds occur at the terminals and the result is a dead short circuit.

The National Board of Underwriters demand that all motor frames be grounded. If this is not done, a person touching the frame

of a motor on which there was a ground would receive a severe shock which might prove fatal with high and medium voltages.

The effects of grounds which have been enumerated above are meant to show exception rather than the rule. While these effects can happen, the usual effect where two grounds occur in a motor on two separate phases is a short circuit as specified in Table II. The same applies where different phases of two or more motors are grounded.

Symptom 5. This is probably the most common fault occurring in polyphase induction motors, as the trouble is not always apparent at a glance. A polyphase induction motor will run single phase indefinitely, once it is up to speed if not loaded beyond the point where it will burn out. The reason why two phases of a star-connected motor and only one phase of a delta-connected motor become hotter than the others is illustrated in Fig. 33. In the star winding, one phase is entirely disconnected, in other words, there is

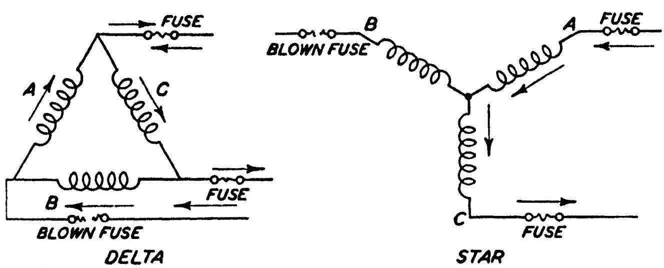


Fig 33 Effect of Single-Phase Operation on Delta- and Star-Connected Windings

no path for the current; while the other two phases are in series, and since these two have to do the work of three, heating of these two will result. In the delta-connected winding, the windings are closed, and if the circuit is broken in line *A*, the current between *B* and *C* will have two paths in parallel, one with one winding, *C* only, and one with two windings, *B* and *A* in series. Consequently, since the current in the series path of *B* and *A* is less than *C*, *C* will heat up. In testing for single-phase operation with a bank of lamps, the lamps will burn full brilliancy on two phases only of a star-connected motor; while in testing a delta-connected motor, the lamps will burn full on one phase only and dim on two phases.

Symptom 6. The trouble, cause, and remedy for this symptom is somewhat like Symptom 4 with the difference that, in this case, the seat of the trouble is more easily found, since fire is usually seen at that point. If the location is not readily found, passing a current through the stator windings with the rotor removed will readily show the location of the trouble.

Symptom 7. When a motor becomes so hot that the frame cannot be touched with comfort, the danger point is about reached, although the mere fact that the human hand cannot bear the heat is not a true indication that the heating has reached a danger point. It is quite safe to operate a motor at a temperature not exceeding 90 degrees C. or 194 degrees F.

Symptom 8. A trouble of this kind is usually caused from moisture which forms a path between the various windings due to the breaking down of the coil insulation. The effect is the presence of hot spots in one or more of the phases, depending on the number of short circuits. While the motor may be placed back in service by cutting out the damaged coils, where there are not too many, it is a better practice to lift the coils and replace them with new ones.

Symptom 9. Where a motor refuses to start when the starter handle is in the operating position, although the motor hums, the trouble may be due to one of three causes, providing the starter or compensator is in working condition. The first cause is due to a blown fuse or inoperative relay and can be easily located by examination of the fuses or relays. If these are intact, the trouble may be due to the bearing being out of true or to a displaced air gap. If the rotor is rubbing the stator, the effectiveness of the flux is impeded and it is impossible for the motor to develop sufficient torque, especially if the motor is a high-speed one. Thus, the symptom leads one to believe the motor is operating single phase. An examination of the air gap with a feeler will usually disclose the trouble; then by adjusting the bearings or replacing them with new ones, the fault is corrected

If this is not the reason for the trouble, the operator can be reasonably assured that there is an open circuit in one of the phases, due to the causes shown in Table II. In case of an open circuit, the motor may be temporarily repaired by jumping the damaged coil, that is, by cutting the damaged coil out of service and connecting

the gap thus caused. Care should be used in an operation of this kind. If the coil is one of the center or group coils and not a phase boundary coil, connecting the two adjacent coils of the same group will put the motor in shape for operating. If, however, the defective coil is a phase boundary coil, care must be used that the phases are not interconnected. Fig. 27 illustrates the method of jumping a phase boundary coil for correct operation.

Where the motor has a two-layer lap winding, the ends of the defective coil thus cut out may be taped and the coil forgotten if none of the layers are short circuited. If, however, any of the layers are short circuited, the coil must be removed. The best method of removing a defective coil, without damaging or interfering with any of the other coils, is to open each layer at each end and pull each strand or layer separately. The space thus left vacant should be filled with wood or some other substance to keep the remaining half coil from chafing against the slot walls due to the internal stresses of electromagnetic induction.

With single-layer or unicoil motors, the complete defective coil must be removed, since circulating currents will flow in the defective coil whether open or closed. These currents will rapidly heat up the coil and ruin those adjacent to it.

Symptoms 10 and 12. These symptoms will not show up unless the motor is carrying around full load. The action is the same as a loose joint in a conductor, that is, the carrying capacity is reduced with consequent heating. Troubles from grounds in modern squirrel-cage rotors are nil, since the bars are grounded. However, some of the older types have the bars insulated from the core and the rings grounded at equidistant points, and a ground in such a rotor will cause a certain amount of unbalance in the currents with consequent heating. If any of the rotor bars are loose, the motor will lose power, and in some cases will run at reduced speed and heat up the stator windings. A ground in the rotor windings of a wound rotor induction motor which are usually star connected, acts in the same manner as described in Symptom 4.

Symptom 13. As stated in Table II, this fault is caused by the rotor magnetic center being out of line with the stator magnetic center. The teeth of the rotor and stator are the exact length and the flux produced by one winding acting on the other holds the center

of the rotor at the exact center of the stator. It is therefore necessary to have a certain amount of end play to allow the rotor to align itself with the stator core. If, in driving a pulley or coupling on the end of the shaft of a motor, the end play is all taken up, the rotor is pulled from the magnetic center of the stator, with the result that the speed of the motor is affected; since the flux, in trying to pull the rotor to its proper place, loses some of its effectiveness for producing power, with the further result that the slip of the motor is increased. Fig. 34 illustrates a case of this kind.

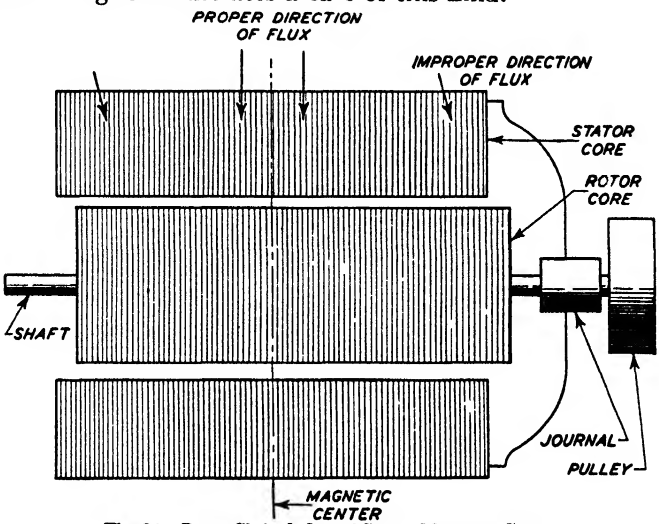
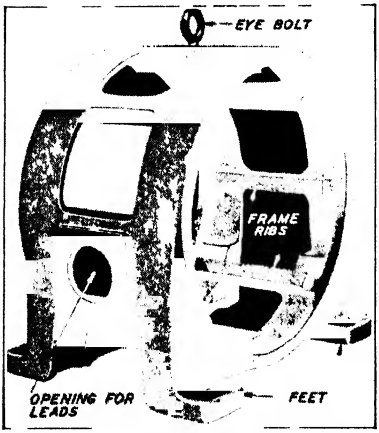
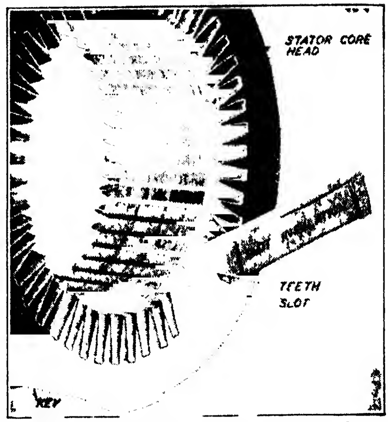


Fig. 34. Rotor Shifted Out of Stator Magnetic Center

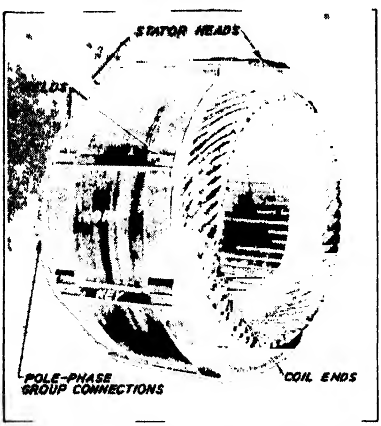
Symptom 14. Where a wound-rotor motor runs at half speed, one of the rotor phases is open circuited. It often happens that the motor will not start in a case of this kind, especially if the motor is heavily loaded. The reason for the half speed is that the effect is the same as if the number of poles is doubled. The windings need not be open to produce this fault, since wearing of the brushes so that they do not touch the collector rings will produce the same effect.



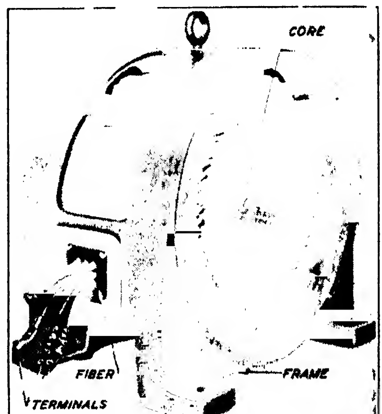
Box type Frame Cast and Machined Ready to Receive the Stator Core



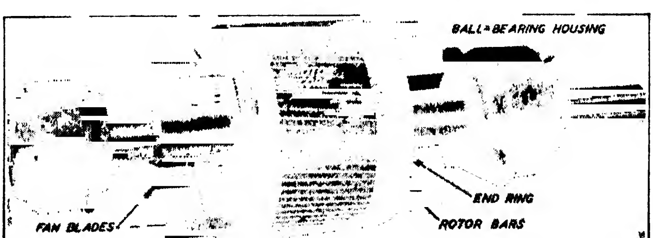
Self locking Slot Insulation Formed from Tough Fibrous Material with Cuff at Each End to Hold it Securely in Place and for Mechanical and Electrical Protection



Complete Pre wound Stator Core Thoroughly Insulated Ready To Be Pressed into the Frame

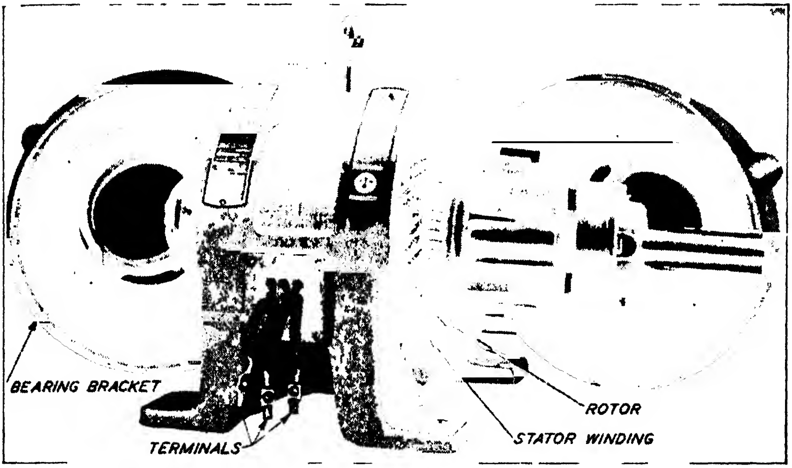


Completely Assembled Stator with Core Pressed in Place and Locked by Means of a Set Screw

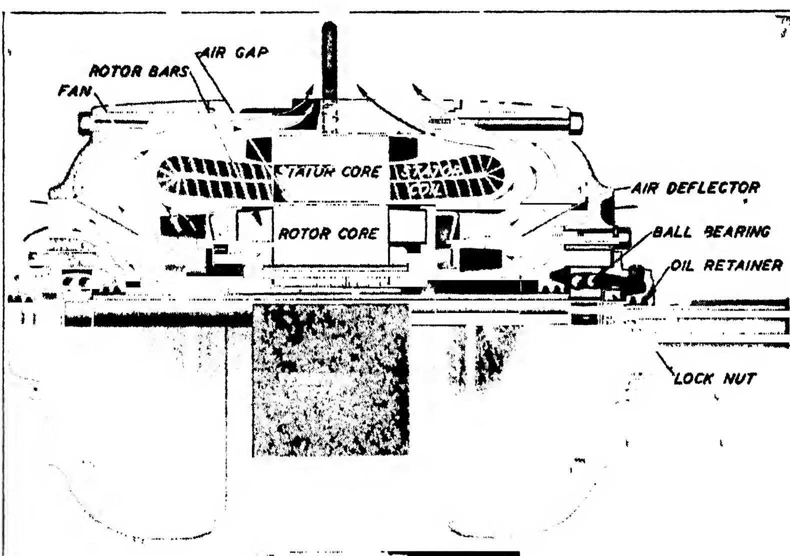


Complete Rotor for a Large Machine Showing Heavy Copper Rotor Bars with a Cast End Ring Brazed in Place

Above Illustrations Courtesy of Fairbanks-Morse & Co, Chicago, Illinois



Large Motor with Bearing Brackets Removed Showing the Motor Intact with Bearings Sealed Fan Blades are Cast Integral with the End Rings



Section through an Open-Frame Type Motor Showing the Squirrel-Cage Rotor and Cartridge-Type Ball Bearing Housing. Curved Arrows Indicate Direction of Air to Cool Motor

Above Illustrations Courtesy of Fairbanks-Morse & Co., Chicago, Illinois

MULTIPLE INSTALLATION OF 500-HORSEPOWER, LOW-SPEED SYNCHRONOUS MOTORS IN A FLOUR MILL, EACH DRIVING A SEPARATE LINE SHAFT THROUGH A MAGNETIC CLUTCH

Courtesy of Fairbanks Morse Company, Chicago

SYNCHRONOUS MOTORS

Installation

Owing to the greater amount of auxiliary equipment required in the installation of a synchronous motor and the delicate nature of most of this equipment, both it and the motor should be installed where it will be free from damage and also convenient for inspection.

When installing large size and medium size synchronous motors, the handling of the different parts is of vital importance. It is necessary in assembling to lift the parts by means of hoists or cranes. Where at all possible rope slings should be used, although cable slings have greater strength for a given size. Be absolutely sure that the slings are of ample strength to handle the load. If the slings are of steel cable, the enamel on the frame may be protected from injury by wrapping the cable with waste where it touches the frame.

Motor sizes up to 250 kilovolt-amperes are usually shipped in one piece, while those having higher ratings are shipped knocked down. In assembling one of the latter, the bed plate is first secured and grouted in, after first being leveled. Next, the bearing pedestals are placed on the bed plate and the one next to the coupling or pulley end firmly bolted down, the other pedestal merely resting on the bed plate. The bearing caps are now removed and the bearings washed out.

The rotor is next set in the bearings and the shaft lined up to ascertain if it is level. When everything is ready for the assembly of the stator, the rotor is suspended with a hoist and the loose pedestal removed. The stator is then suspended over the end of the shaft and moved as far as the sling supporting the rotor will allow. The rotor is then blocked with wooden blocking placed inside the stator and the sling moved to the end of the rotor shaft so as to allow the stator to be moved to its position. The blocking is then removed and the stator placed in position.

The bed plate is usually provided with slots to allow the stator to be pinched in place with crow bars, so that the rotor and stator windings are not damaged. After the stator is in place, the pedestal is put back in place and the bearing caps replaced.

The air gap is then checked to see if the same space exists between the rotor and stator around the whole periphery. Shims of various thicknesses of sheet iron are sent with the machine for the

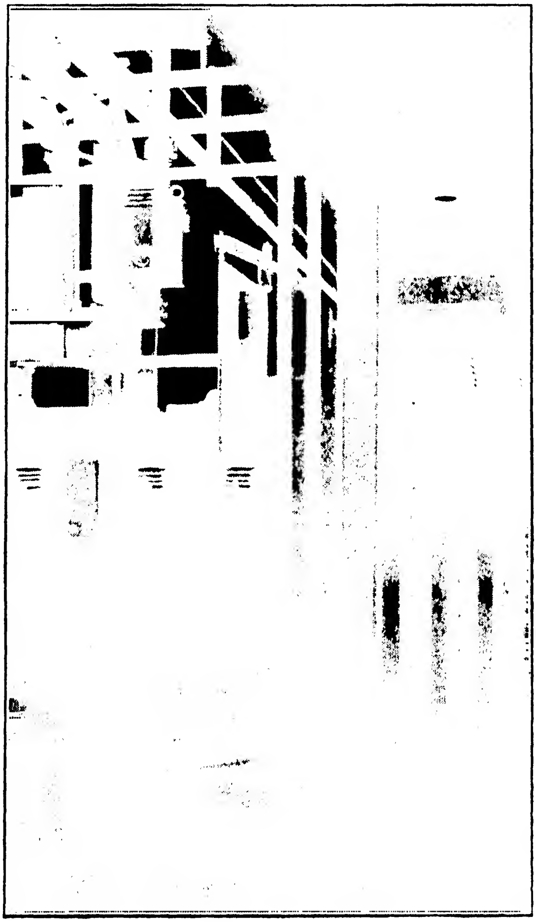


Fig. 1. Layout of Connections between the Oil Circuit Breakers and a Synchronous Motor, Showing the Method of Connecting the Lead Covered Cables to the Bus through Potheads

purpose of adjusting the air gap. The bearings are again washed with kerosene and filled with the proper grade of oil up to the height of the oil gauges. The motor is then ready to operate, after being connected to the line.

The motor should be run light for some time in order to allow the bearings to be run in, check the bearing temperatures, and the no-load operating conditions. After being reasonably assured that everything is O.K., the load may be connected.

The drive should be given as much attention as the assembly of the motor. If the load is gear driven, the gears must mesh properly; if belt driven, the center line of each pulley must coincide. If direct connected to the load, both coupling faces must be true and at right angles with the center line of their respective shafts before being aligned. The outside of both halves of the coupling should be concentric with the center of the shaft. In connecting the two halves of the coupling, care must be used that the end play is not all taken up. There should be just enough end play to allow the rotor to float back and forth in order to establish its magnetic center with respect to the stator.

The exciters of synchronous motors are either belt, gear, or direct drive, where each motor has its separate exciter; while where there are several motors in a line, it is usual to excite the fields of all motors from a motor-generator set.

The installation of feeders for synchronous motors up to approximately 250 kilovolt-amperes may be accomplished in the same manner as for induction motors, and up to 550 volts may utilize rubber-covered cables run in conduit. On sizes exceeding the above rating practically one-third of the motor is below the surface of the floor; and on all installations above 440 volts, lead-covered cables should be used. These cables should terminate in potheads, as shown in Fig. 1.

Methods of control

The wiring connections of a synchronous motor depend almost entirely on the method of control, of which there are several. Among the most important are

(1) Control by reduced voltage, manual start and stop.
(2) Control by reduced voltage, automatic start and stop.
(3) Control by full voltage, across the line, automatic start and stop.
(4) Control by auxiliary prime mover.

Reduced voltage manual control. Fig. 2 illustrates the wiring connections of a 550-volt motor for reduced voltage starting and

manual control. With this type of control, two oil circuit breakers enclosed in one tank are required. The exciter is direct connected to the motor; there is no exciter switch; and the excitation of the

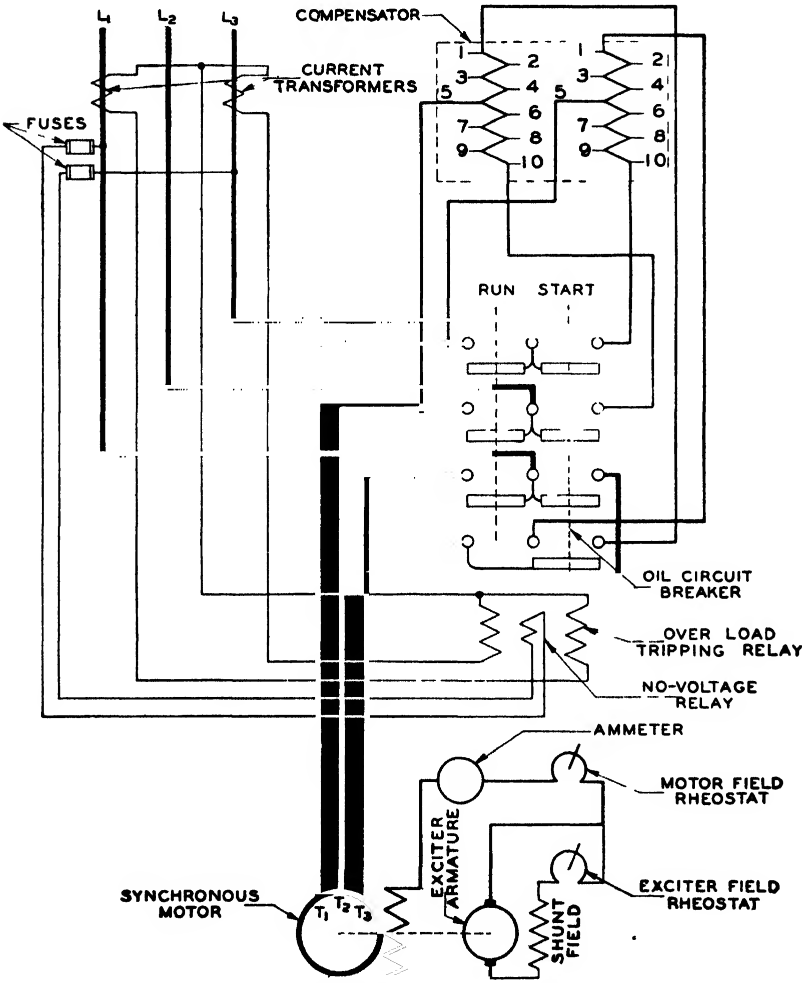


Fig. 2. Wiring Diagram of Connections for a 550-Volt Synchronous Motor for Reduced Voltage and Manual Starting

motor field takes place as the motor comes up to speed. The compensator is provided with several taps in order to increase or decrease the starting torque of the motor, as the case might be. The panel instruments consist of an alternating-current ammeter and a direct-

current ammeter. The diagram also shows the location of the motor field rheostat, the exciter shunt field, exciter field rheostat, current transformer, exciter armature, and ammeter.

When starting up a synchronous motor connected as shown in Fig. 2, the following rules should be observed:

(1) See that both starting and running switches are open.

(2) Adjust the motor field and the exciter field rheostats with all the resistance in series with their respective fields.

(3) Close the motor starting switch, which at reduced voltage should bring the motor up to approximately 75 per cent of synchronous speed in from 20 to 30 seconds.

(4) Adjust the motor field and exciter field rheostats until the current taken by the motor is minimum.

(5) Open the starting switch and close the running switch at the same time. These switches are interlocked so that it is impossible to close both at the same time if properly adjusted.

(6) Adjust the two rheostats until the proper value of current in the motor is reached and the proper amount of excitation applied.

In shutting down or stopping the motor, the following rules must be observed:

(1) Open the motor running switch.

(2) Adjust both motor and exciter field rheostats to zero or with the resistance all in series.

The conditions to guard against during starting and running a synchronous motor are: overloads; overheating of the amortisseur or squirrel-cage winding; loss of excitation; and single-phase operation.

Fig. 3 shows the wiring diagram of another method of reduced voltage starting and manual control. With this method, three circuit breakers are required. As shown in the diagram, the two starting breakers are connected each side of the compensator and are closed together. Excitation is applied after the motor has attained approximately synchronous speed. The symbols in this diagram have the following meanings: *CT*—current transformer; *PT*—potential transformer; *A*—ammeter; *WM*—wattmeter; *PFM*—power factor meter; *NVR*—no-volt-relay; *Dis. Res.*—field discharge resistance; *F.D.S.*—field discharge switch; *AS*—ammeter switch; *TC*—trip coils; *O. relay*—overload relay; *FR*—exciter field rheostat; *Gen. FR*—generator field rheostat.

The following rules must be observed in starting up and shutting down a motor with the type of control shown in Fig. 3:

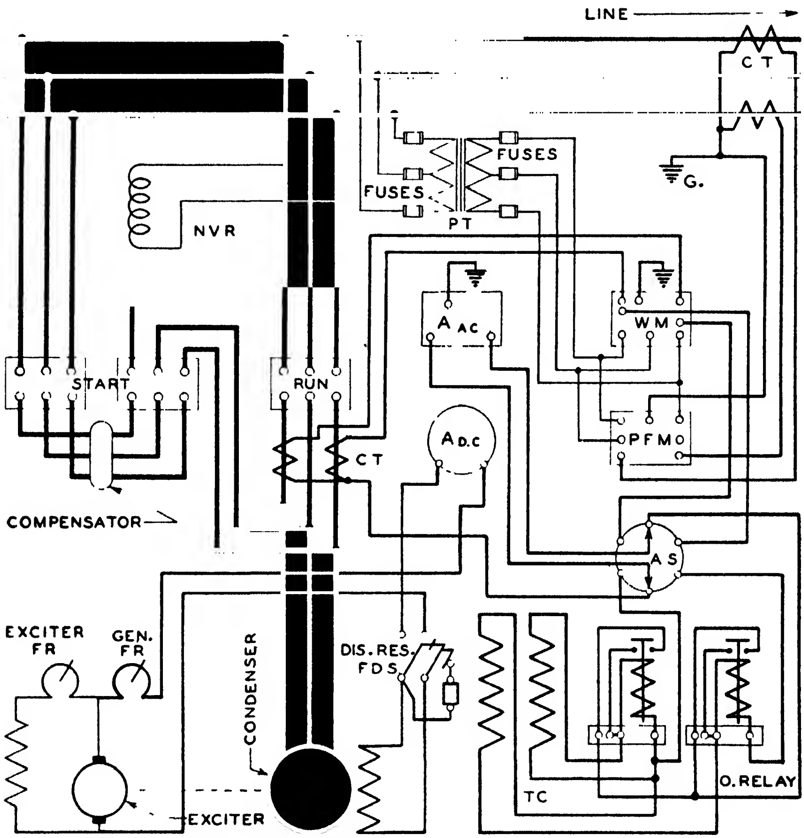


Fig. 3. Diagram of Connections Showing Another Method of Connecting a Synchronous Motor for Reduced Voltage Starting and Manual Control

(1) See that all switches, on both motor and exciter, are open.

(2) Make sure the discharge switch is in the proper position so that the induced current in the motor field is short circuited through the discharge resistance.

(3) Adjust the motor field rheostat with all the resistance in series with the field.

(4) Close the motor starting switch. which with reduced voltage should allow the motor to reach approximately 75 per cent of synchronous speed in from 20 to 30 seconds.

(5) Close the field switch, connecting the exciter circuit to the motor field, first making sure that the exciter circuit is alive, which is usually indicated by a pilot light or a voltmeter. If the motor fields are properly excited, it will be indicated by a peculiar sound made by the motor which increases and decreases in volume. This sound is due to the hunting effect of the motor.

(6) Adjust both motor field and exciter field rheostats until the hunting practically ceases and the current drawn by the motor windings is minimum.

(7) Open the starting switch and close the running switch. These switches are interlocked against closing both at the same time.

(8) Adjust the resistance of both the exciter and motor field rheostats until the desired load and power factor are obtained.

In shutting down or stopping the motor, the following rules must be observed:

(1) Open the motor running switch

(2) Adjust the excitation of the motor field by cutting in the resistance of the motor field rheostat.

(3) Adjust the exciter voltage through the exciter field rheostat to a minimum.

(4) Open the field switch so that the current in the motor field is discharged through the discharge resistance.

Reduced voltage automatic control. The wiring diagram of a synchronous motor panel for reduced-voltage starting push-button control is shown in Fig. 4. This control differs from that shown in Fig. 9 by the addition of two starting circuit breakers connecting the autotransformers to the motor and to the line and two induction time or hesitating relays for changing from starting to running. These relays are called control relays in the diagram.

With this control, as soon as the starting button is depressed, the solenoids on the two starting breakers are energized. At the same time the induction time relay controlling the starting breakers is also energized. As the motor accelerates and approaches synchronism this relay closes the field switch after the motor current has reached a predetermined value, thus applying excitation to the motor. This causes the motor to speed up and pull in step, after which the running breaker control relay, which is energized by the closing of the *PQ 29* relay which in turn is energized from the battery bus, closes. On its closing, the closing coil of the running breaker also closes and closes the breaker at the same time putting the motor on the line.

On overload, the overload relays function the same as for across-the-line starting. For stopping, the running breaker is tripped by the

energizing of the opening or trip coil which is connected to the stop button and fed from the battery circuit.

Full voltage automatic control. Across-the-line starting, which came in practice in 1925, has practically superseded all other methods

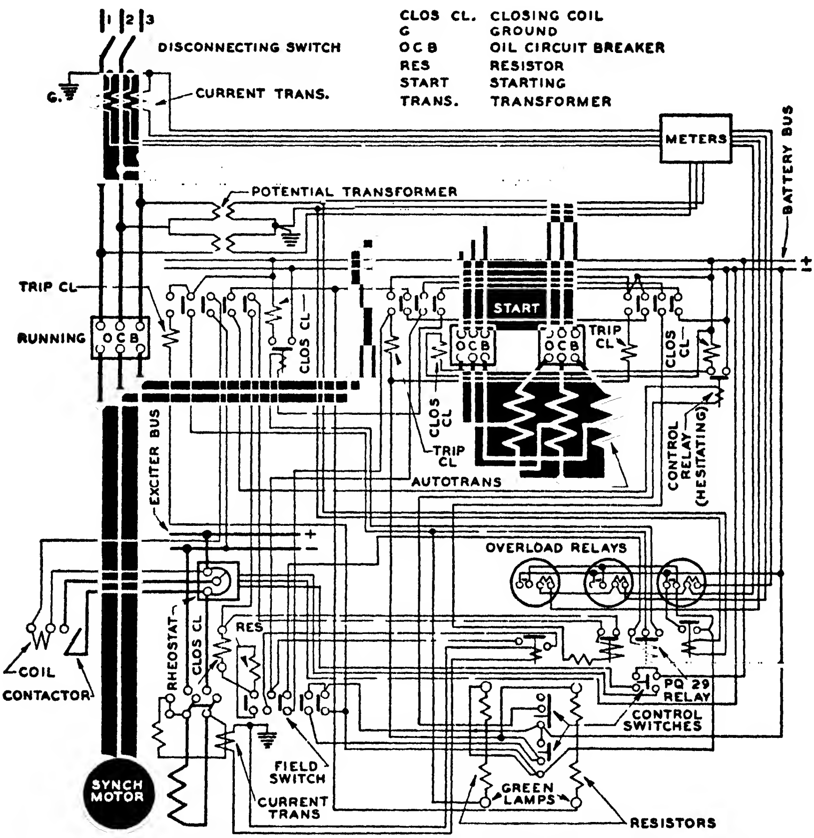


Fig 4. Wiring Diagram of a Synchronous Motor Panel for Reduced Voltage Starting, Push Button Control

of starting synchronous motors having low speeds. Starting by this method requires considerable more control equipment and it is almost essential that the control be automatic. Fig. 5 shows the wiring diagram for full automatic, across-the-line starting for motors up to 300 kilovolt-amperes and voltages up to 600 volts. This method of starting was brought about by the development of a new type of synchronous motor drawing a low starting current, having a high

efficiency, and requiring low excitation with a uniform accelerating torque. These developments made it unnecessary to have a skilled operator on the job all of the time. As stated above, only the low-speed types can be started in this manner; the high-speed and medium

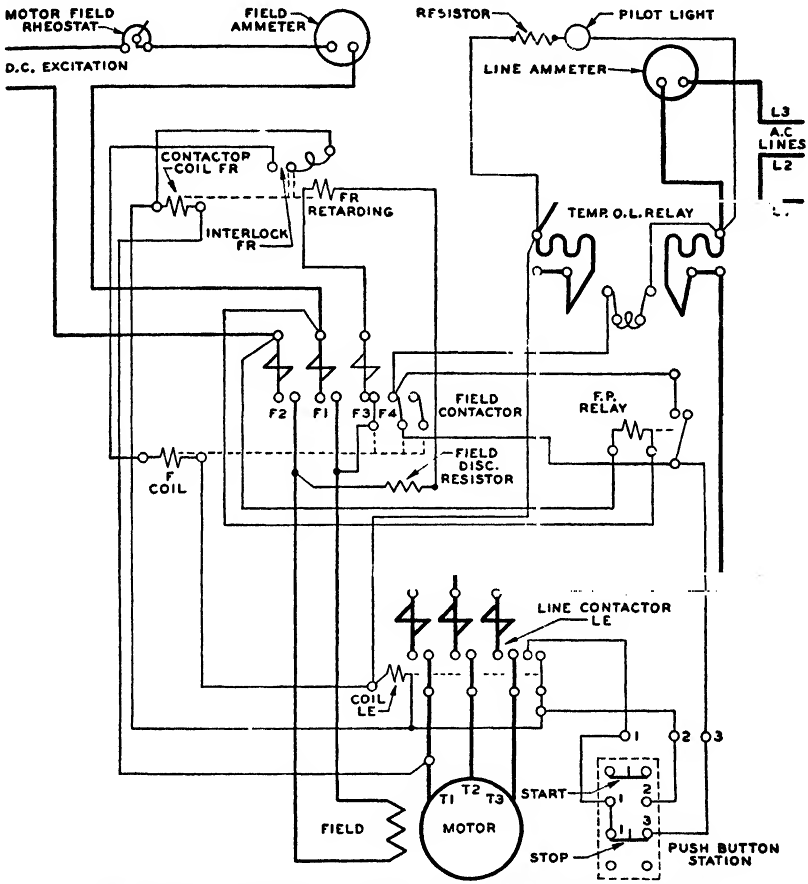


Fig. 5. Wiring Diagram for Full Automatic Across-the-Line Starter for a Synchronous Motor

speed motors requiring reduced voltage although automatic. It is only a question of time, however, before medium-speed and high-speed synchronous motors can be started across-the-line.

In order to explain the functions of starting a synchronous motor automatically, either with reduced voltage or across-the-line, some

of the main characteristics of the motor should be thoroughly understood. A synchronous motor is not unlike a squirrel-cage induction motor in one respect. For instance, during the starting period, the amortisseur winding of the synchronous motor serves the same purpose as the squirrel-cage winding of the induction motor, both producing a starting torque in practically the same manner. From this point on they are dissimilar, the synchronous motor requiring one more function—the application of direct-current excitation to its field—to complete the starting operation.

Where voltage is applied to the stator windings of a synchronous motor which has its field windings short circuited through a discharge resistance, an alternating voltage is induced in the field winding, this voltage having a frequency corresponding to the speed of the motor. At rest, the rotor or field frequency is the same as the frequency of the voltage impressed on the stator windings. This frequency decreases as the motor speeds up until, at synchronous speed, the frequency of the rotor is zero. At the same time the frequency is decreasing due to increase in acceleration, the induced voltage is also decreasing, the combination of decreasing voltage and frequency producing practically a constant induced field current up to approximately 75 per cent of synchronous speed. From this point on, the induced field current rapidly decreases and is also zero at synchronism. It is therefore at a point between 75 per cent and 100 per cent of synchronous speed that field excitation may be applied.

Advantage of the decreasing frequency and decreasing induced field can be taken by utilizing relays that function through the effect of both. There are several types of frequency and induced field relays.

One type of frequency relay consists of an armature actuated by a relay coil of high resistance and low inductance connected in parallel with a reactance coil of low resistance and high inductance. When voltage is impressed on the motor windings, the current induced in the motor field causes the frequency relay to pick up due to the high impedance of the reactance coil and thus diverting the majority of the induced current through the windings of the frequency relay coil. As the motor accelerates, the frequency of the induced field voltage decreases, allowing the induced current to flow through the reactance coil, causing the frequency relay to drop out and allow-

ing the field current to be applied to the motor field. In connection with this frequency relay, there is also a time element which functions independent of the motor speed, thus making it possible to set the time of applying the field current at a value sufficient to allow the motor to reach its highest speed.

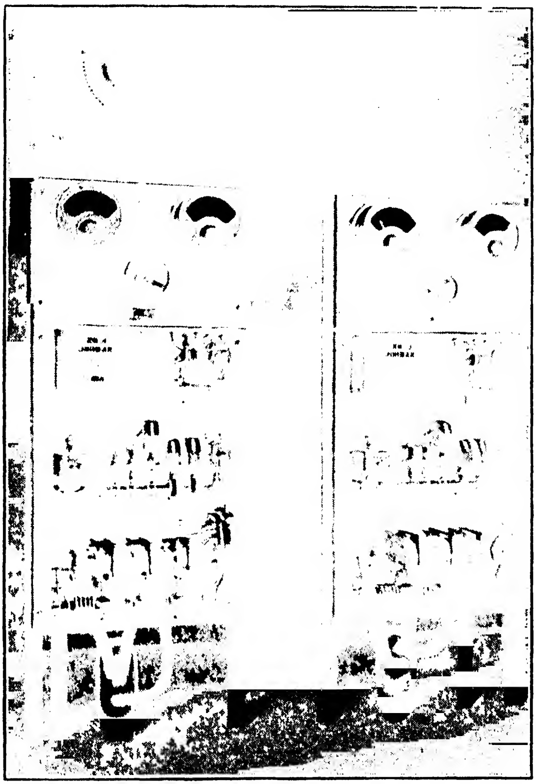


Fig. 6 Two Across-the-Line Starting Panels for Medium Rating Medium Voltage Synchronous Motors

One type of induced field relay has two pairs of contacts—one to make contact and the other to break contact. It also has two electromagnets—one operating on direct current and connected to the source of excitation and the other operating on alternating current but connected to the motor field circuit during the starting period. As the motor increases in speed, the current in the relay coil, which is alternating, decreases in value until the force acting on the same

coil by the direct current overcomes the force due to the alternating current and causes the relay to operate and apply direct-current excitation to the motor field.

Another type of field relay acts on a diminishing induced field current. It consists of a contactor armature on which is mounted a magnetic time interlock. When the contactor coil is energized, the interlock has a tendency to close, but is prevented from closing by a retarding coil connected in series with the motor field winding and which is energized by the induced current in the motor field winding. As the motor increases in speed, the induced current decreases; and

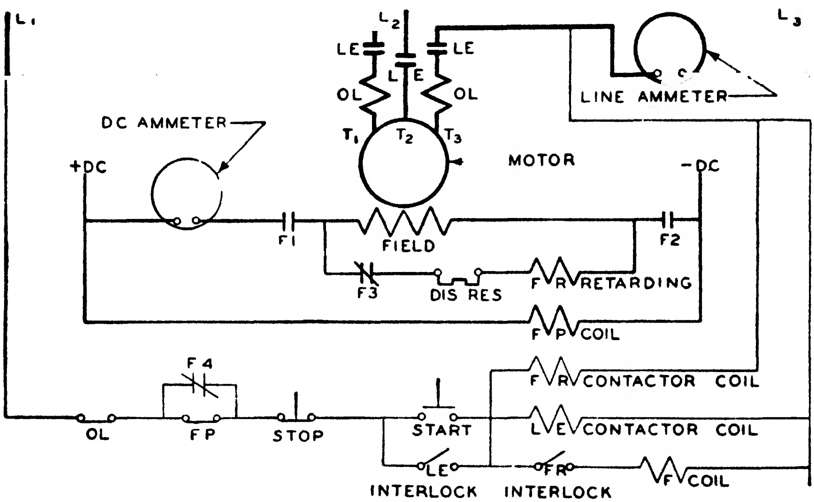


Fig 7 One Line Diagram of Across-the-Line Starter for a Synchronous Motor

as the speed of the motor approaches synchronism, the relay opens, allowing the interlock to close applying excitation to the motor field after a brief delay. This delay allows the relay to be set to trip at the highest speed which the motor can attain under the worst conditions, and at the same time allows a certain interval of time before applying excitation under normal operating conditions. This type of field relay is used in the diagram of Fig. 5. The panel and equipment for this diagram are shown in Fig. 6. The equipment mounted on this panel consists of a line contactor, a field contactor, a field protective relay, a temperature overload relay, a rheostat operating mechanism, a line ammeter, a field ammeter and a pilot light for indicating line voltage.

"A simplified one-line wiring diagram of this automatic across-the-line starter is shown in Fig. 7, and the symbols on the diagram are used in the following description of the method of starting and stopping.

"When the start button is closed, the line contactor coil *LE* is energized, closing the line contactor and connecting *L1*, *L2*, and *L3* to the motor terminals. The interlock *LE* closes at the same time as the contactor and forms a holding circuit for the line contactor so that the push button may be released.

"While the motor is increasing in speed, the field circuit is closed through the normally closed pole *F3* of the field contactor, through the discharge resistor and the retarding coil *FR* of the field relay. This holds the interlock *FR* open until the motor approaches synchronism.

"At the time the line contactor *LE* closes, the contactor coil *FR* is energized and tends to close the interlock *FR*. As the motor accelerates, the induced alternating-field current through the retarding coil *FR* decreases and releases the interlock *FR* when the motor approaches synchronism.

"After a few seconds delay, the interlock *FR* closes, energizing the contactor coil *F*, causing *F1* and *F2* to close and *F3* and *F4* to open. The closing of *F1* and *F2* applies excitation to the motor field, which completes the starting operation. The opening of *F3* opens the discharge circuit of the motor field. The opening of *F4* allows *FP* to open and shut down the equipment in case of voltage failure in the exciter circuit. *FP* must have closed its contacts before the field contactor opens *F4*, necessitating that excitation voltage be available before attempting to apply field to the motor.

"Merely pressing the stop button shuts down the motor by opening all contacts that are closed and closing those contacts which are normally open when the motor is running."*

Fig. 8 is a wiring diagram for one of the panels shown in Fig. 9, which illustrates the panels for the control of two full automatic across-the-line starters for synchronous motors of high rating and voltages up to 2200 volts. The operation of starting and stopping merely consists of pressing a start button for starting and a stop button for stopping. When ready to start a synchronous motor with this control, the following rules should be observed:

(1) See that power is on the panel, which will be indicated by the green pilot lamp *45* burning bright.

(2) See that direct-current excitation and 125-volt storage-battery control power are on the panel, which will be indicated by contactor *32* picking up, which in turn closes a contact and energizes the low-voltage relay *30*. If either source of direct-current supply is off, the panel contactor *32* will not close.

(3) The red and white pilot lamps must both be dark before attempting to start.

The operation of the panel relays and contactors is in the following sequence:

*This data is from a G. E. Instruction Book.

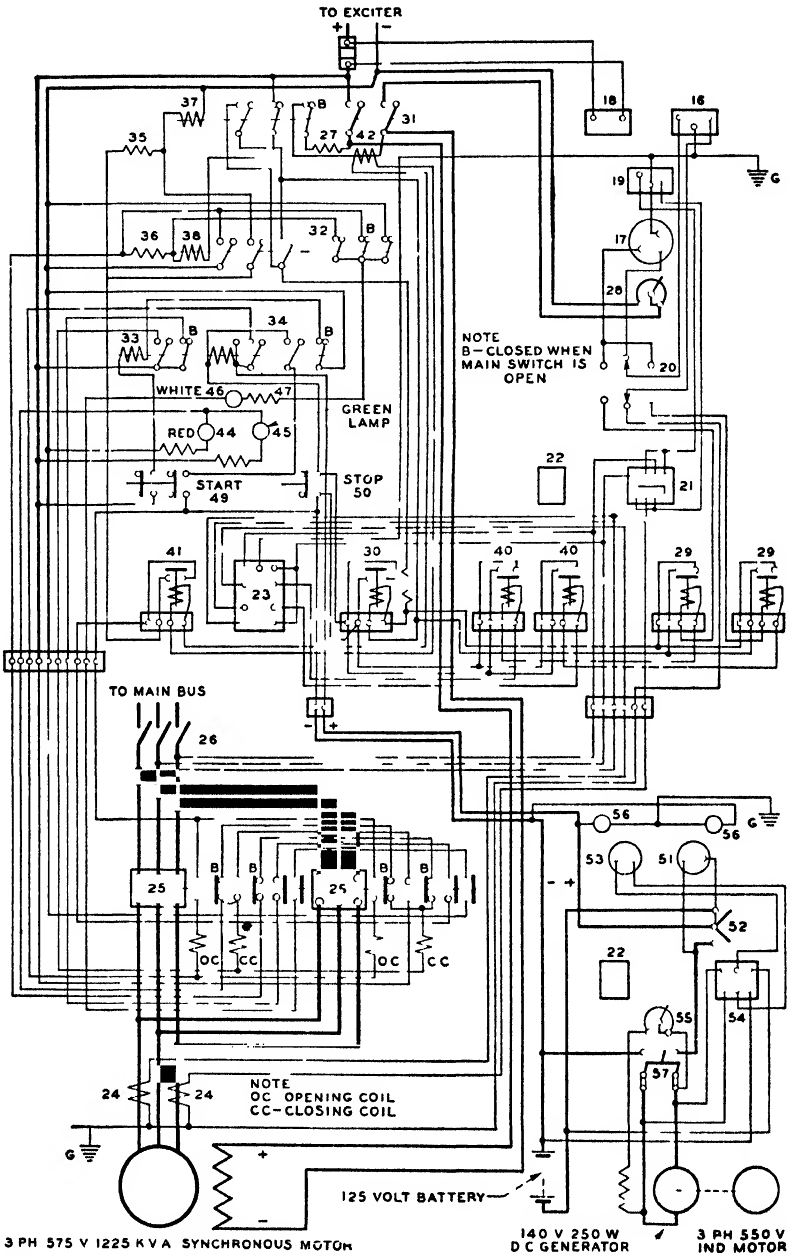


Fig 8 Wiring Diagram of Connections for Full Automatic Across the Line Starter for Synchronous Motor Having a High Rating (See table on page 15 for description of part numbers)

BILL OF MATERIAL

Part No.	Quantity	
16	1	H 5—5-ampere ammeter--2000 ampere scale
17	1	C R 2—5 ampere curve drawing ammeter
18	1	D H 5—100-ampere field ammeter
19	1	H 5 —750-volt voltmeter
20	1	3-way ammeter jack
21	1	8-point potential receptacle
22	2	4-point potential plugs
23	1	D S 6 550-volt 5-ampere watthour meter
24	2	2000-ampere K50 current transformers
25	2	T.P.S.T. 7500-volt 1000-ampere K12 O.C.B.
26	3	S.P. 2000-ampere disconnecting switches
27	1	Field discharge resistance
28	1	Hand wheel and chain operating mechanism
29	2	S P. instantaneous P.Q. overload relays (starting)
30	1	550-volt P.Q. 25 low voltage relay
31	1	C R. 2810—1269—A 150-ampere 250-volt contactor
32	1	C R. 2810—1353 – F 75-ampere 250-volt contactor
33	1	C.R. 2800—1132—J1 D.C. shunt 125-volt contactor
34	1	C R. 2800—1112—A2 D C. shunt 125-volt contactor
35	1	C R. 3158 resistors 600 ohms for part No. 31
36	1	C R. 9158 resistors 1000 ohms for part No. 32
37	1	Coil for part 31
38	1	Coil for part 32
39		
40	2	S P. Instantaneous P. Q relays (running)
41	1	P.Q. 33-relay current limiting (closes exciter circuit)
42	1	15-ampere W2 current transformer
43		
44	1	Indicating lamp receptacle with ruby lenses
45	1	Indicating lamp receptacle with green lenses
46	1	Indicating lamp receptacle with clear lenses
47	1	C.R. 9158 resistor for part No. 46.
48	3	170-volt 15-watt lamps for parts 44, 45, and 46
49	1	C.R. 2940—BS211—C-J push button for starting duty only
50	1	C.R. 2940—BS211—A push button for stopping duty only
51	1	3-ampere D.R. 2-ammeter with double stop
52	1	S P.D.T. 250-volt 100-ampere ammeter transfer switch
53	1	100- to 150-volt D R. 2-Y voltmeter
54	1	6-point potential receptacle
55	1	Back of panel field rheostat mechanism
56	2	Ground detector lamp receptacles
57	1	D P.S T. 250-volt 60-ampere lever switch

(1) "Depressing the start button *49* energizes the coil of the solenoid control contactor *33*, which throws the two solenoid closing coils of the oil circuit breakers *25* in series on the 250-volt exciter bus through the two main con-

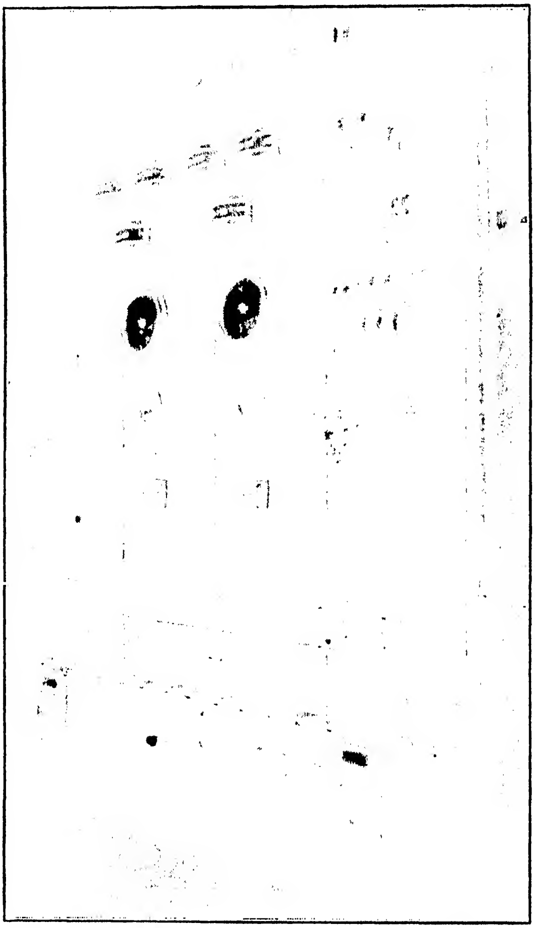


Fig. 9. Across-the-Line Starting Panels for Two Large Size Synchronous Motors

tacts on contactor *33*. (NOTE: 250-volt excitation is usually used unless otherwise specified.)

(2) "The auxiliary contact on *33* opens when *33* itself closes. This auxiliary switch circuit opens the field contactor *31* coil circuit so that the latter cannot close until *33* opens, nor can *31* close (because of auxiliary switches on the circuit breakers *25*) until both breakers are closed.

(3) "As the closing coils of the solenoids have been energized under step

No. 1 of the sequence, the circuit breakers will close applying A.C. power to the motor. At this point the green pilot lamp is dark, while the red pilot lamp is bright.

(4) "As soon as the power is applied to the motor, the A.C. current induced in the motor field flows through the current transformer *42*, the 'B' auxiliary switch on contactor *31* and through the discharge resistance *27*. The induced current in *42* immediately picks up relay *41* (which is instantaneous circuit opening and delayed circuit closing) which opens up coil circuit *31*.

(5) "Relay *41* is held open until the motor comes up to approximately synchronous speed, then *41* closes, completing the circuit through coil *31*, through an auxiliary switch on either breaker, and through a 'B' auxiliary switch on *33*. *31* is now closed, applying direct-current excitation to the motor field which is now running in synchronism, indicated by the white lamp on the panel. At this point load may be applied to the motor. When the motor is operating properly, the red and white pilot lamps are burning while the green pilot lamp is dark.

(6) "To stop, depress the stop button *50*, which energizes the coil circuit of *34*, which in turn picks up and completes the circuit from the 125-volt battery through the main contacts on *34*, the two 'A' auxiliary switches on the circuit breakers *25*, and the opening coils of the solenoids.

(7) "On ordinary overloads, the two right-hand relays *29* operate instantaneously through the coil of the low-voltage relay *30*, which has a time-limit feature. On a short circuit, the overload relays *40* operate instantaneously by short circuiting the contact of the low-voltage relay *30*, which in turn energizes the coil of the tripping contactor *34*, and the contactor operating closes the tripping circuit and opens the circuit breakers *25*."*

Auxiliary prime mover control. A synchronous motor can be started by means of a small induction motor which brings it up to near synchronous speed; after which it can be thrown direct across the line. This method of starting applies to alternators which are to be converted for use as motors. In starting by this method, the speed of the synchronous motor should not exceed the synchronous speed; in fact it is better to be slightly lower, since it is much easier to bring a motor into step when approaching synchronism than when above. A motor started in this manner can carry no mechanical load while starting. Excitation may be applied either before or after the motor is on the line. The power required is approximately one horsepower for every 10 kilovolt-amperes of motor rating.

Another method of starting by an auxiliary prime mover, where a source of direct current is available, is illustrated in Fig. 10. This method consists of utilizing the exciter as a prime mover. The operation is as follows: The double-throw switch, marked *2* in

*Courtesy of Canadian General Electric Company.

the diagram, is closed in the upper position impressing direct voltage on the exciter which now operates as a motor. The armature resistance is then cut out through the starting box and the motor accelerates to full speed. After full speed is attained (which in this case is approximately 10 revolutions below synchronous speed), the synchronizing lamps will commence to flicker, at which time it is safe to throw the motor across the line through the three-pole oil

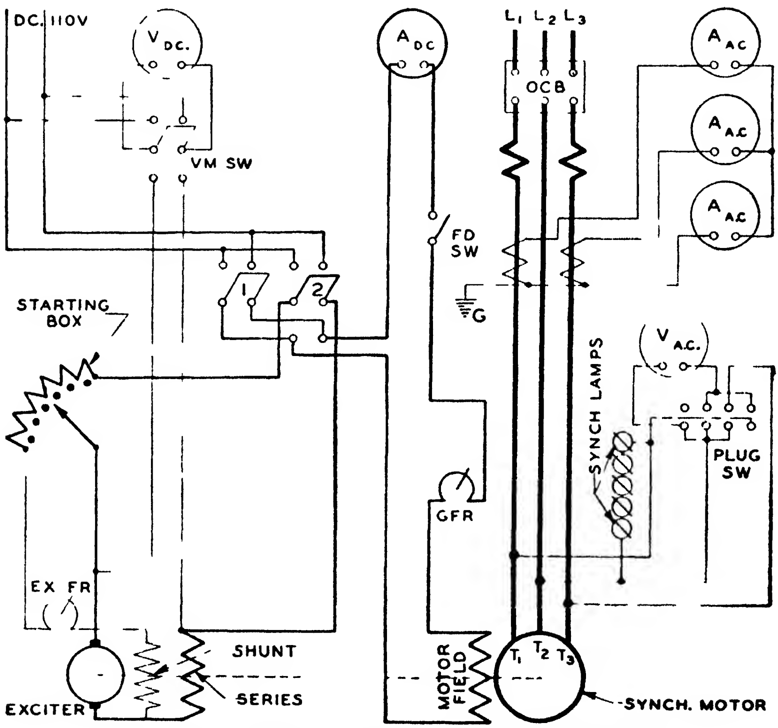


Fig 10 Wiring Diagram for Operating an Alternator Not Equipped with Amortisseur Windings

switch connected to the station bus. The motor now speeds up and will probably hunt until the double-throw switch is thrown to the bottom position when the exciter is changed from a motor to its proper function as an exciter. The field current is then adjusted to load and power factor of the motor.

A synchronous motor can be started at the same time the alternating-current generator that will supply current to the motor is

started. This method is sometimes employed as an emergency or where the motor rating is nearly as great as the rating of the alternator. As the alternator is started, the motor is also started by pulling on the belt or by some similar means; and as the alternator accelerates, the motor keeps in step with it until synchronous speed is reached. A motor thus started can carry no mechanical load until synchronous speed is reached and the field is excited.

Operating instructions

Owing to the greater amount of auxiliary equipment, a synchronous motor needs more care and attention than an induction motor. When a synchronous motor has an individual exciter, there are two distinct machines to service, one direct and the other a combination of direct and alternating. In order to keep these in proper running condition, the following rules should be observed:

(1) Inspect the motor, exciter, and control at least once a day.

(2) Keep all of the above equipment and the room in which it is housed absolutely clean.

(3) See that the bearings are not leaking and allowing the oil to come in contact with the windings of either machine or the exciter commutator.

(4) Keep the commutator of the exciter true and undercut.

(5) See that the brushes on the commutator and motor collector rings are free to move in their holders.

(6) See that the motor overload relays are set at a value which will protect the motor in case of an overload.

(7) See that the motor has the proper amount of excitation; that its power factor is not too low, either leading or lagging.

(8) Examine the air gaps of both machines at least once a month to ascertain if the bearings are wearing.

(9) Change the oil in all bearings at least every six months, or oftener if motor is operating in a damp or dusty location.

(10) If the motor is direct connected to its load, see that there is sufficient end play so that the motor will float and maintain its true magnetic center with respect to the rotor and stator.

(11) Change the leads to the collector rings at least every six months. This allows both to wear down at the same rate. The positive collector ring wears down much faster than the negative ring.

Troubles of synchronous motors

Table I shows the usual troubles of synchronous motors in tabulated form for ready reference and following the tabular matter is a discussion of some of these troubles.

TABLE I

Troubles of Synchronous Motors

Symptom	Trouble	Cause	Remedy
1. Hot bearing	(a) Bearing dry	(a) Not sufficient oil	(a) Refill with clean oil, after washing bearing with kerosene.
	(b) Bearing dirty	(b) Dust or dirt in oil	(b) Refill with clean oil, after washing bearing with kerosene.
	(c) Bearing tight	(c) Not sufficient oil, or dust or dirt in oil, or particles of metal sheared off and deposited at other parts	(c) Scrape bearing and shaft or replace bearing. (NOTE: Never use ice or water on a hot bearing unless the motor is kept running as it is liable to spring the shaft.)
	(d) Oil rings not working	(d) Rings out of slots	(d) Replace rings, making sure no metal adheres to sides of slots. If rings stick or run slowly, bevel at either top or bottom with a fine file.
	(e) Bearing binding	(e) Shaft out of true	(e) Place shaft in a lathe and true and renew bearing.
	(f) Bearing out of true	(f) Too much strain on pulley	(f) Bearing should be shimmed with thin pieces of tin as a temporary expedient, or replaced by a new one.
	(g) Loose bearing	(g) Vibration	(g) Tighten set screws holding bearing in journal.
2. Bearing hot, but no hotter than other parts of motor	Heat transferred from rotor or stator windings	(a) Overload on motor	(a) Decrease load or increase size of motor.
		(b) Motor field over-excited	(b) Decrease strength of field by lowering the excitation.
3. Stator windings hot at certain spots to cause smoking; wedges over coils charred	Displaced air gap, or rotor not centered in stator (NOTE: Owing to the air gap of a synchronous motor being greater than in an induction motor, this trouble is seldom met with, although the bearings may become worn.)	Bearings worn on one side	If noticed before coils are damaged, realigning the bearing and inserting new wedges will correct the fault, otherwise coils will need to be replaced.

TABLE I—Continued

Troubles of Synchronous Motors

Symptom	Trouble	Cause	Remedy
4. Motor fails to start	(a) Not sufficient torque	(a) Voltage too low	(a) Increase the line voltage. The torque is increased or decreased as the square of the applied voltage, i.e., if the voltage is doubled, the torque is increased four times. The starting torque of a motor having reduced voltage, starting is increased by raising the compensator taps.
	(b) Open circuit in stator windings	(b) Due to a short circuit, rough handling, etc.	(b) Repair break by "jumping" the damaged coil or coils, or replace damaged coils.
	(c) Friction	(c) Bearings too tight	(c) Loosen bearing caps and, if the trouble persists, scrape the bearing.
	(d) Overload	(d) Mechanical load too great	(d) Remove part of the load or install a clutch coupling between motor and load.
	(e) Wrong connection in compensator	(e) One phase reversed or carelessness	(e) Test out and make proper connection.
	(f) Motor trying to start single phase	(f) One line open; contacts on circuit breaker burned off	(f) Test out line or repair circuit breaker.
	(g) Solenoid circuit not functioning (NOTE: Applies to automatic starting.)	(g) (1) Battery circuit open or battery fully discharged (NOTE: Applies to automatic starting.)	(g) (1) Test battery circuit. Test voltage of battery, and if low, recharge. Clean all contacts.
		(2) Operating arms holding; circuit making and breaking contacts not working properly	(2) Lubricate the operating arm bearings and see that they fall into their neutral position.
		(3) Contacts dirty or burned	(3) Contacts should be cleaned once every week.

TABLE I—Continued

Troubles of Synchronous Motors

Symptom	Trouble	Cause	Remedy
5. Motor starts but fails to come up to speed	Not sufficient torque	(a) Rotor field in circuit with exciter, due to discharge switch being in wrong position. This creates a separate flux which opposes the alternating flux in the stator windings	(a) Open the circuit between the exciter and motor field windings.
		(b) Mechanical load too great	(b) (1) Open discharge resistance. (NOTE: Care must be exercised in employing this method, and the resistance circuit must be closed before shutting down, otherwise the field windings may be damaged.) (2) Raise the line voltage. (3) Increase the squirrel-cage windings on the rotor. (4) Install clutch between motor and load.
		(c) Not enough bridges or bars in squirrel-cage winding	(c) Install clutch between motor and load.
6. (a) Motor comes up to synchronous speed but cannot be thrown on the line	Trouble in exciter circuit	(a) Open circuit in rotor field	(a) Test out with low voltage or magneto and repair the break.
(b) Motor fails to synchronize		(b) Open circuit in exciter field	(b) Test out with low voltage or magneto and repair the break.
(c) Circuit breaker trips out when line voltage is impressed on motor		(c) Open circuit between exciter and motor field	(c) Test out with low voltage or magneto and repair the break.
		(d) Open circuit in exciter armature (NOTE: The circuit between rotor and exciter is not broken in a case of this kind, but the current is interrupted and decreased.)	(d) Bridge the open circuit by connecting the commutator bars each side of break.

TABLE I—Continued

Troubles of Synchronous Motors

Symptom	Trouble	Cause	Remedy
		(e) Faulty brushes on exciter causing the same trouble as above stated	(e) Adjust brushes if out of line, renew if broken or worn; increase tension of brushes and clean the commutator.
		(f) Open circuit in motor field rheostat	(f) Test with a magneto and repair break.
		(g) Open circuit in exciter field rheostat	(g) Test with a magneto and repair break.
		(h) Field discharge switch fails to make proper contact	(h) Clean contacts and, if badly pitted, renew.
		(i) Short circuit in one or more field coils	(i) Test with low voltage and compass, and repair or renew damaged coil or coils.
		(j) Reversed coil in rotor field circuit. (NOTE A fault of this kind cannot happen while the motor is running, but would be due to a wrong connection while repairs were being made to the rotor All of the other faults could happen, however, while the motor was running, due to careless operation, or from foreign material being drawn into the motor by suction, or by damage to the exciter and wiring	(j) Test with low voltage and compass, and reverse connections of coil causing the trouble. NOTE In connection with the above two remedies, low direct-current voltage is applied to the field windings and a compass held to each pole. In case of a short circuit, the short-circuited pole will give no deflection of the needle. With a reversed coil, the deflection is opposite to what it should be, in other words, instead of adjacent north and south poles, there will be two north or two south poles together.)

TABLE I—Continued

Troubles of Synchronous Motors

Symptom	Trouble	Cause	Remedy
7. Stator windings hot at all parts	(a) Mechanical overload (b) Low power factor	(a) Mechanical overload (b) Overexcitation of field coils (NOTE: The low power factor in this case is leading, and has the same effect as low lagging power factor, since the current and voltage are out of phase in the same proportion.)	(a) Remove part of load or increase size of motor. (b) Adjust field excitation until the stator current reaches a value where further adjustment will increase its value. This will increase the power factor of the motor, but will lower the power factor of the system.
8. One or more coils in stator so hot that the insulation is burned	Short circuit in one or more coils	Due to mechanical injury or broken-down insulation, due to overheating	"Jump" the injured coil as a temporary expedient, or replace with a new coil.
9. Motor issues a peculiar humming sound which increases and decreases in volume at certain intervals (NOTE: Motor may even slow down and stop, or trip the circuit breaker in a case of this kind.)	Motor "hunting"	(a) Unstable speed of prime mover on alternator supplying the motor (b) High resistance in line. Only found on excessively long transmission lines	(a) If speed of prime mover cannot be properly regulated, adding more bars to the squirrel-cage winding will correct the fault. (b) If speed of prime mover cannot be properly regulated, adding more bars to the squirrel-cage winding will correct the fault.
10. Motor issues a harsh buzzing sound which remains constant in value	(a) Short-circuited coil or group (b) Open circuit	(a) Due to mechanical injury or broken-down insulation due to overheating (b) Due to mechanical injury or broken-down insulation or due to a short circuit which will burn out the coil and cause an open circuit	(a) Jump the injured coil as a temporary expedient, or replace with a new coil. (b) Jump the injured coil as a temporary expedient, or replace with a new coil.

TABLE I—Continued

Troubles of Synchronous Motors

Symptom	Trouble	Cause	Remedy
	(c) Grounds. One ground might cause a heavy current to flow in the grounded phase, depending on what part of the winding the ground occurred	(c) Dampness, or mechanical injury or broken-down insulation	(c) Remove ground as soon as possible by lifting affected coil, and reinsulate. One ground is not always serious but is liable to cause others, and two grounds in the same motor is a short circuit.
	(d) Reversed coil or group	(d) Due to wrong connection during repairs (NOTE: A reversed coil or group will not prevent a motor from starting, coming up to speed and running.)	(d) Test with low voltage direct current and a compass, and change the connections on the reversed coil or group.
11. Motor trips its circuit breaker and shuts down, although the induction motors on the same system remain running	(a) Surge on line	(a) (1) Momentary high voltage due to speeding up of alternator (2) Lightning	(a) No remedy. Line usually rights itself in a few seconds, after which the motor can be again started.
	(b) Low voltage	(b) (1) Momentary slowing down of alternator (2) Short circuit on line.	(b) (1) No remedy. Line usually rights itself in a few seconds, after which the motor can be again started. (2) No remedy. Line usually rights itself in a few seconds, after which the motor can be again started.
	(c) Excitation ceases while motor is carrying a heavy mechanical load	(c) (1) Open circuit between exciter and motor field	(c) (1) If the exciter voltmeter shows a reading, the trouble is either in the motor field, in the motor field rheostat, or in the wiring between the exciter and motor field. Test out the various parts of the circuit with a magneto or Megger and repair.
		(2) Exciter not operating	(2) If exciter voltmeter does not show a reading, the trouble is in the exciter. Examine the brushes, test the field coils with low voltage or a magneto, test the armature for open circuit and test the exciter field rheostat, and repair.

TABLE I—Continued

Troubles of Synchronous Motors

Symptom	Trouble	Cause	Remedy
12. Motor issues a loud growling sound, easily distinguished from those mentioned above, and motor acts as if overloaded, although the direct-current meters show no over-excitation and motor is running light	Rotor out of stator magnetic center	(a) Motor not level	(a) Level the motor bed plate.
		(b) Shaft collars shifted. Too great end play of shaft.	(b) Adjust collars for proper end play. (NOTE The cores of synchronous motors are narrow in comparison with induction motors.)

Symptom 2. *Transfer of heat from rotor or stator windings.* Over-excitation of the motor field causes the motor to operate at a low leading power factor, which is wasteful of energy and overloads the motor.

Symptom 4. (a) *Voltage too low.* Where reduced voltage starting is employed, it is usual to use a starting voltage of from one-half to two-thirds line voltage. If, however, the line voltage is low, it will affect the torque of the motor, since the torque increases or decreases as the square of the applied voltage. Assuming the torque at full line voltage is 250 pounds feet at 550 volts, the torque at one-half voltage is $\frac{275^2}{550^2}$ times 250 equals 62.5 pounds feet. Thus while the voltage is reduced one-half, the torque is quartered, since $250 \div 62.5$ equals 4.

If the motor will not start with the compensator taps in their original position and the load is off the motor, raising the compensator taps to a higher value will usually remedy the fault. If, however, the motor still will not start, the only remedy is to raise the line voltage if it is at all low.

(b) *Open circuit in stator windings.* The cause and remedy for this fault are the same as for induction motors.

(c) *Friction of bearings too great.* This may be caused from overheating, due to grit in the oil or shaft out of alignment.

(d) *Mechanical load too great.* A synchronous motor, unless specially designed, is not able to start under load conditions owing to its low starting torque. Synchronous motors are better adapted for starting loads that increase as the speed of the motor increases, such as centrifugal pumps or where the load is not applied until after the motor is on the line, such as pulp grinders, etc. Thus if the mechanical load is too great, installing a clutch coupling will remedy the fault.

(e) *Wrong connections in compensator.* In connecting up a compensator, care must be used that the phases are not reversed, since a reversed phase in the compensator acts much the same as a reversed phase in the motor. The result is to lower the starting torque and a defect of this kind will be noticed by unbalanced ammeter readings. In order to determine the source of trouble, the rotor must be revolved by some method, such as an auxiliary motor, since

at standstill the currents are unequal even if the connections are correct. Another method of obtaining balanced readings and thus locating any unbalance and the source of trouble is to move the rotor to successive points on each phase, as shown in Fig. 11. The correct and wrong connections between a motor and compensator

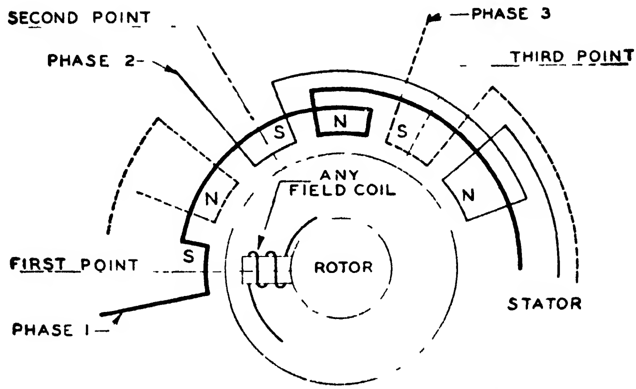


Fig 11 Method of Obtaining Balanced Readings in the Field Coils of a Synchronous Motor

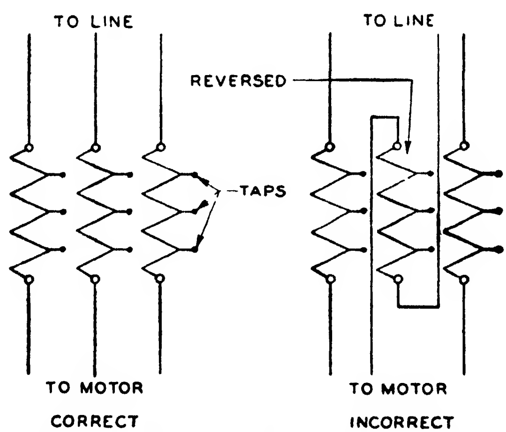


Fig. 12. Diagram of Correct and Wrong Methods of Connecting Compensator Windings

are shown in Fig. 12. A reversed phase in the stator windings is remedied in the same way as for an induction motor.

(f) *Single-phase operation.* This trouble is not always apparent and the whole circuit must be tested out until the offending unit is located. Tests may be accomplished with a Megger, magneto, volt-

meter, or a bank of lamps. In making the test for open circuit in the starting equipment, a start is made at the disconnecting switches. If voltage is at this point, the oil circuit breakers or line and starting contactors, as the case may be, are next tested. If there is no voltage at this point, the contacts are carefully examined and will no doubt be badly burned. If, however, the circuit breakers test O.K., the trouble is in the leads between the circuit breakers and the compensator or between the compensator and the motor. Testing each part of the circuit separately will disclose the source of trouble.

(g) *Solenoid circuit not functioning.* This fault is encountered on automatically started synchronous motors only. The start and stop circuits are fed from storage battery mains at 125 volts and the trouble will be found either in the battery itself or in the contacts, or in the closing coil circuit which is fed from the exciter circuit, or due to mechanical trouble such as operating arms holding or circuit making and breaking contacts not working properly.

If the battery is low when tested with a voltmeter, it should be immediately recharged. If the battery circuit is open at any point, it must be traced and the break repaired. If the trouble cannot be traced at these points, the conclusion is that the contacts are dirty. In any event, these contacts should be sandpapered at least once a week, and oftener if they become pitted or burned or if the equipment is installed in a damp or dusty location. If the trouble rests with any of the mechanical parts, such as the operating arms, it will be readily noticed by the solenoids being unable to close the breakers.

Symptom 5. (a) *Rotor or field in circuit with the exciter.* The field switch should be open to the exciter circuit but closed through the discharge resistance so as to short circuit and kill the induced current in the field coils when the motor is being started up. Excitation should never be applied to the field windings until the motor approaches synchronism, since if applied with full voltage at any speed below 75 per cent of synchronous speed, the motor may actually lose speed.

In the wiring of synchronous motors it has been shown that, in some instances, the motor fields are permanently connected to the exciter circuit, but in these instances the field resistance is all cut in the circuit and full field excitation is not applied until the motor is in synchronism and on the line.

(b) *Mechanical load too great.* There are four methods of remedying a fault of this kind.

(1) By opening the discharge resistance circuit. This method is simple but might be fraught with disastrous results through carelessness. On most synchronous-motor installations the discharge switch is so constructed that when the fields are not on the exciter, they are short circuited through the discharge resistance, and there is no open circuit through the field. Adding a single-pole, single-throw switch in series with the discharge resistance, as in Fig. 13, has the following effect. Opening this switch allows the induced current to build up in the field winding as the motor comes up to

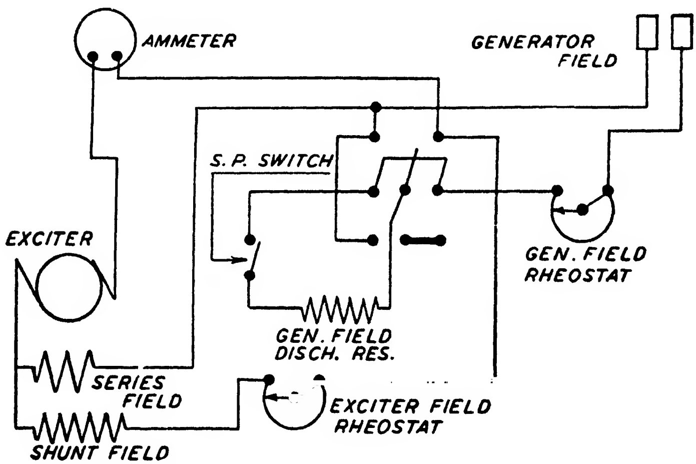


Fig. 13 Method of Connecting a Discharge Resistance to Expedite the Starting of a Low Torque Motor

speed. This current is alternating and acts in the same manner as the current induced in the rotor of an induction motor. After the motor has reached synchronism and has been thrown on the line, the field is connected directly to the exciter, the operation being performed quickly in order to kill the induced current in the field windings; otherwise either or both the field and exciter armature windings may be injured. The single-throw switch must then be closed for, if it is left open, on shutting down the motor the field windings might be seriously damaged from the heavy current flowing in them. This is a makeshift method but should never be attempted unless the motor is under the supervision of a skilled operator.

(2) By raising the line voltage. This method will correct the difficulty but might interfere with the equipment of other consumers on the same line.

(3) By increasing the rotor squirrel-cage or amortisseur winding. This is the most practical of all the various remedies. A synchronous motor may start under fair load conditions, but when reaching a certain speed, usually around two-thirds of synchronous speed, the speed ceases to increase. An instance of this is in starting a synchronous motor direct connected to a centrifugal pump. As the speed increases, the load of the pump also increases and the torque not being

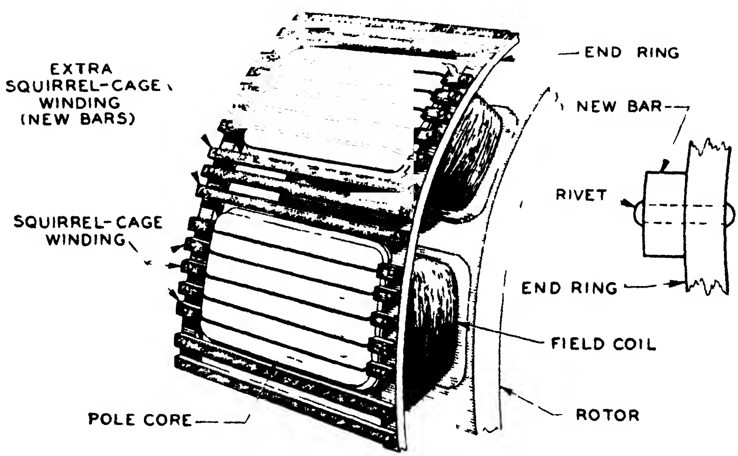


Fig. 14 Showing How to Increase the Starting Torque of a Synchronous Motor by Increasing the Bars in the Amortisseur or Squirrel-Cage Winding of the Rotor

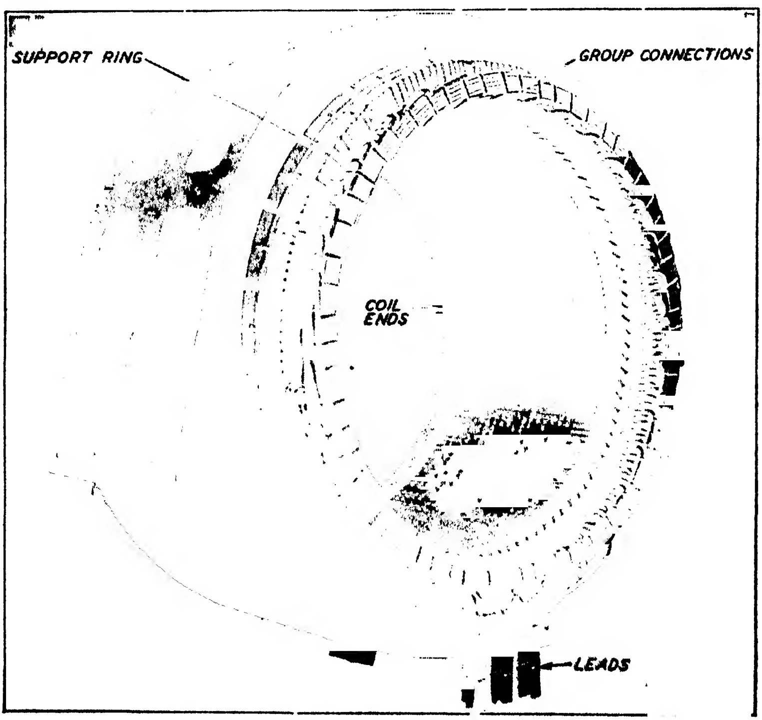
great enough to overcome the extra load, the motor speed cannot increase. The remedy consists of adding extra bars to the squirrel-cage winding, as shown in Fig. 14.

(4) By installing a clutch coupling. This is an expensive method but is effective, since the motor can always be started with no load.

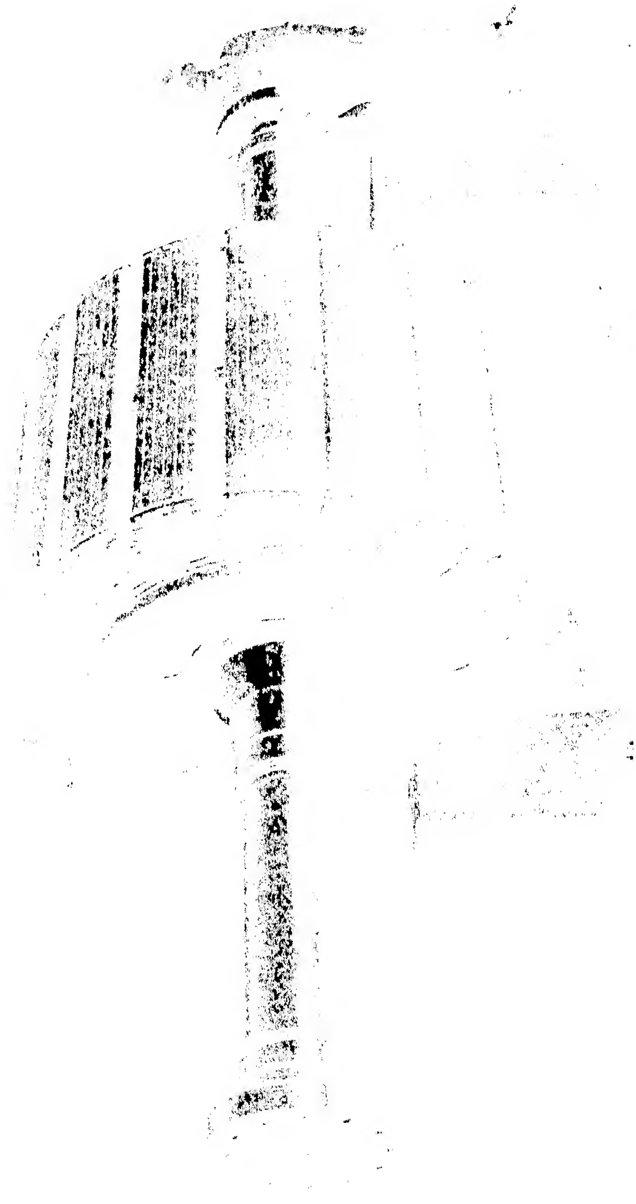
Symptom 9. *Motor hunting.* Hunting of a synchronous motor is due to unstable speed of prime mover driving the alternator supplying the motor, or to high line resistance. While the latter is seldom encountered, the former is quite common. Since the synchronous motor derives its name from the fact that it travels in synchronism

with the alternator supplying it, it is also a fact that if the speed of the alternator varies, the speed of the motor will also vary, this variation being called hunting. As the speed of an alternator varies, the frequency also varies; and it often happens where the motor is carrying a heavy load that it cannot accelerate and keep in step with the alternator when changing from a low frequency to a higher frequency. When a motor fails in this respect, it loses speed and will eventually stop; and unless the breakers open, the windings will be burned out by the heavy rush of current.

Symptom 11. Either a *surge on the line* or *low voltage* may cause a synchronous motor to trip out, the symptom being the same as hunting *Failure of excitation* may not cause a motor to drop out if the motor is running without load, but when loaded it will operate as an induction motor and will therefore slip in speed and eventually come to a standstill, usually with disastrous results.

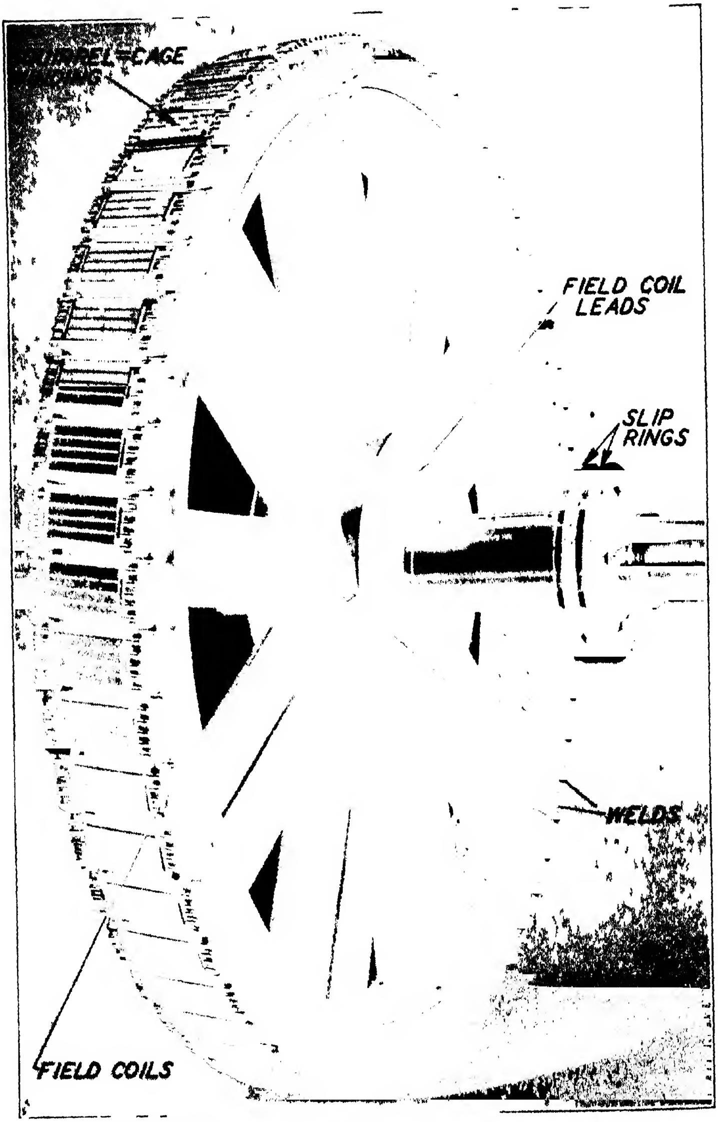


STATOR OF A LARGE SYNCHRONOUS MOTOR
Courtesy of Allis-Chalmers Manufacturing Co., Milwaukee, Wisconsin



ROTOR FOR AN 8850 H. P., 360 R. P. M., SYNCHRONOUS MOTOR FOR DRIVING A STEEL MILL MOTOR GENERATOR SET

Courtesy of Allis-Chalmers Manufacturing Co., Milwaukee, Wisconsin



LARGE SLOW-SPEED ROTOR HAVING WELDED STRUCTURAL STEEL SPIDER

Courtesy of Allis-Chalmers Manufacturing Co., Milwaukee, Wisconsin

ALTERNATING-CURRENT MOTOR STARTERS

In order to fully understand the type, selection, and application of alternating current motor starters, it is necessary to review the types of motors involved.

The first division, naturally, would be that of single-phase and polyphase motors.

The types of **Single-Phase** motors generally used are:

Shaded pole motors
Split-phase motors
Capacitor type motors
Universal motors
Repulsion-induction (R.I.) motors

The types of **Polyphase** motors generally used are:

Squirrel-Cage motors
Slip-ring or wound rotor motors
Synchronous motors

Types of Starters. Manual starters, where the connecting of the motor and acceleration is under the control of an operator.

Semiautomatic starters, where the connecting of the motor and acceleration is under the control of the operator, but the actual switching is accomplished by automatic means.

Automatic starters, where the connecting of the motor and the acceleration is automatic and the initiation of the starting process is accomplished by pilot devices such as push buttons, pressure or temperature switches, and float switches.

The main functions of a starter are:

1. Connecting the motor to the line and disconnecting it when motor is to stop.

2. Reversing the motor, where reversing of the driven machine is required.

3. Protecting the motor from overloads.

Illustrations by courtesy of Allen-Bradley Company, Milwaukee, Wis.

4. Disconnecting the motor from the line in case of voltage failure.

There are, of course, other functions for which starting equipments are used, such as plugging motors to a quick stop in connection with machine tool controls, operating several motors in sequence in connection with conveying equipment, chemical processes, assembly lines, and machine operation.

SINGLE-PHASE MOTOR STARTERS

Shaded Pole Motor. Control equipment for shaded pole motors, since they are made only in small sizes, consist mainly of some small switching equipment, such as ordinary snap switches, in case of manual control. Where control is automatic, small relays or a pilot device can be used. One of the main applications for this equipment is found in valve and damper operation; small fans can also be driven by this type of motor.

Split-Phase Motors. Control equipment for split-phase motors is also limited to low horsepower requirements such as washing and ironing machines, small household pumps, etc. They are hardly ever built for higher than ¼ horsepower due to the high current inrush on starting. Most power companies will permit this type of motor only on intermittent loads, because of the bad voltage effect on their distribution lines. All starting equipments used with these types of single-phase motors connect the motor directly to the line, Fig. 1. These motors have a starting and a running winding; after the motor has reached about ⅔ speed, an internal centrifugal switch cuts out the starting winding. Due to the high current inrush which may reach seven to eight times normal full-load current which these motors take, switching equipment has to be carefully selected, especially where automatic control is involved, and manufacturers will often limit the capacity of their equipment to ⅛ horsepower in case of split-phase motors, especially where frequent operation can be expected.

It is well to keep in mind that the split-phase motor has a low starting torque and that both power factor and efficiency are low—around 65 per cent.

Capacitor Motors. Control equipment for capacitor type motors is not quite so simple even though the fundamental construction of

the motor is the same as that of the split-phase motor; that is to say, the motor has a starting and a running winding. As the name implies, the motor uses a condenser in the circuit. For some motors the same condenser is used for starting and running. Other motors use a condenser only during starting and run as induction motors. Some

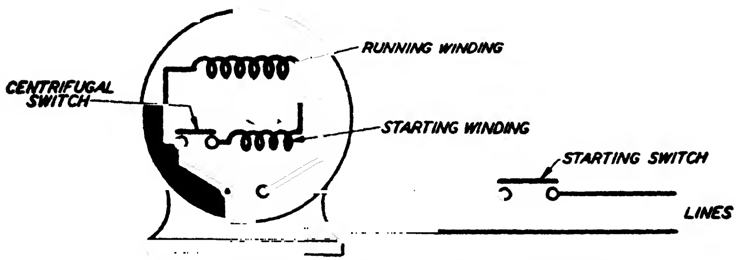


Fig. 1. Diagram of Internal Circuits of Split-Phase Motor

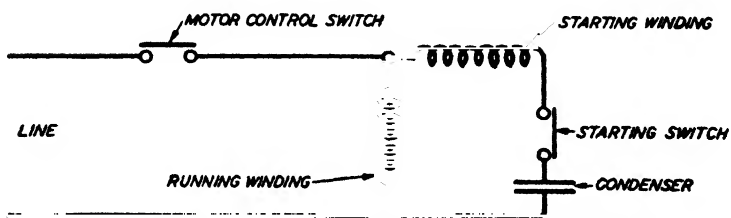


Fig. 2. Schematic Diagram of the Capacitor Start Split-Phase Motor

motors use one condenser value for starting and another value for running.

The capacitor type motor has a starting and a running winding, Fig. 2. The starting winding has a condenser connected in series. As the motor is coming up to speed, the starting winding and the condenser are cut out of the circuit. This can be accomplished either by a centrifugal switch inside the motor or by an outside switch which is a part of the motor control equipment. After the starting winding is disconnected, the motor runs as an induction motor.

The starting switch can be operated manually in connection with the motor starter if it is of the manual type or by a relay, which can be either current or voltage operated if the starting equipment is automatic.

This motor has a high starting torque at low starting current. The full-load performance is the same as that of a split-phase

motor. In this type motor, Fig. 3, the condenser can be used in connection with an autotransformer in order to reduce the required condenser capacity.

A motor which uses the same size condenser for starting and running does not have to have a starting switch, Fig. 4. The condenser is connected in series with one winding, as shown in diagram. This type of motor is used primarily for intermittent service and can

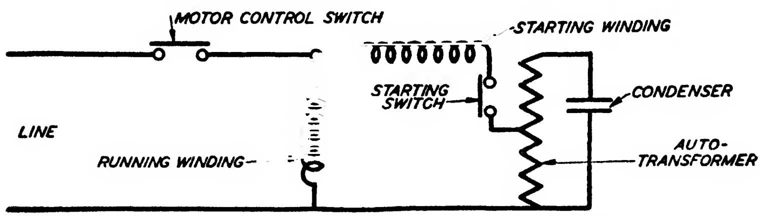


Fig 3 Schematic Diagram of Capacitor Start Motor Using Autotransformer to Boost the Condenser Voltage During Starting Period

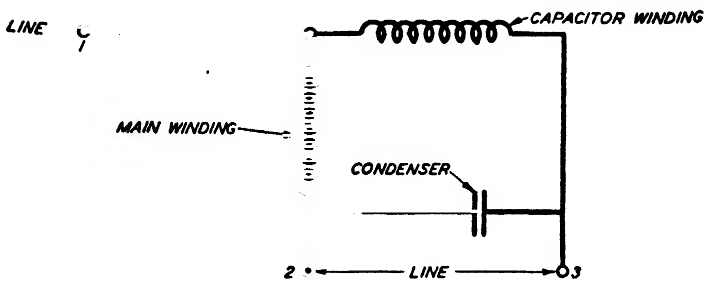


Fig. 4. Schematic Diagram of a Capacitor Motor in Which the Condenser Is in the Circuit During Starting and Running Periods

also be used for reversing. In one direction of rotation the line is connected to 1 and 2; for reverse direction to 1 and 3. A transformer can be used in connection with this motor in order to reduce the size of the condenser.

These types of motors are essential single-voltage motors and cannot be adapted to dual voltage (110, 220 volts) readily without complications.

Most applications of the capacitor motors are found in connection with household refrigerators, oil burners, stokers, and household pumps and are today of great importance and serve to reduce line disturbance.

Where an internal centrifugal starting switch is used, an out-

side starting relay is not required—a motor control switch, which in its simplest form may be a snap switch, will be sufficient. Where motor protection against overload is wanted, a small single- or two-pole auxiliary breaker can be used, Fig. 5. For motors larger than 1 horsepower rating an outside starting switch is used. The switch may be time, current, or voltage operated. If manual control is

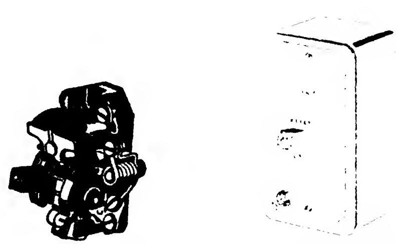


Fig. 5. Fractional Horsepower Starting Switch and Thermal Overload Circuit Breaker

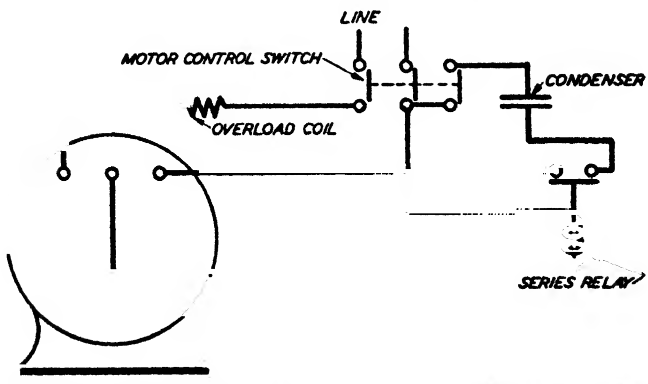


Fig. 6. Connection Diagram of a Capacitor Start Motor with a Series Relay for Connecting the Condenser in Series with the Starting Winding

used, a three-pole switch is necessary for the control and the method of connection is as shown in Fig. 6.

Capacitor motors can also be used in reversing service. Fig. 7 illustrates and describes the method of connection used.

Where automatic control by means of push button, pressure, or float switch is indicated an automatic starter will be required, and, depending on the size of the motor, either across-the-line starting or starting with a step of resistance to reduce the current taken from the line.

Universal Motors. As the name implies, universal motors can be used for alternating current and direct current. These motors are primarily fractional horsepower motors, and their maximum size

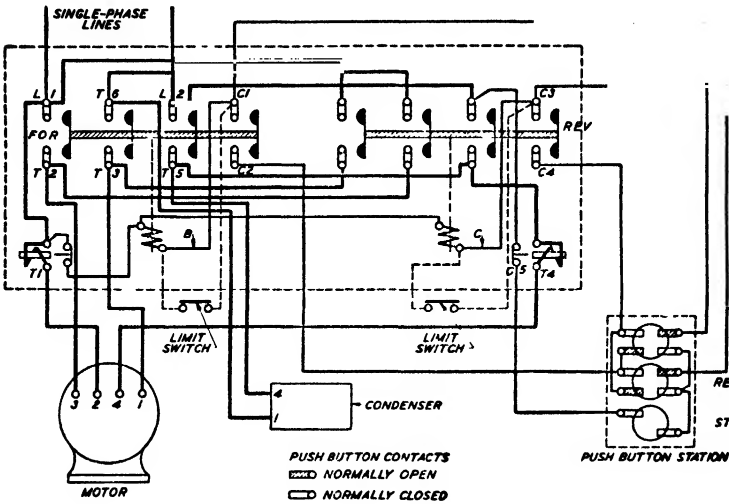


Fig. 7. Wiring Diagram of a Push-Button Automatic Reversing Controller Used for a Capacitor Motor

Pressing the push button marked *For* (forward) causes current to flow from the terminal *L1*, through the overload contacts *T1* and through the contactor coil *B* to terminal *C1*, across the crosshatch contacts of the forward push button, diagonally through the "Normally Closed" contacts of the *Rev* (reversing) button through the closed contacts of the stop button through the overload trip contacts *C5* to terminal *L2* of the line. Current going through the contactor coil *B* moves the four contactors on the crosshatched bar marked *For.* to the left, connecting *L1* of the line directly to terminal *3* of the motor.

Current flows through the motor winding from 3 to *1* to terminal *T3*, across the contactor to *T6*, through the condenser terminals *1* to 4 to terminal *T5* and line *L2*. This winding has the condenser connected in series with it. There is another circuit from *L1* through the overload coil *T1* to terminal *2* of the motor.

The current flows out of terminal *4* of the motor through the overload coil *T4* to terminal *T5* and across the contactor to line *L2*.

Pushing the stop button stops the flow of current through the control circuit and coil *B*, shutting down the motor.

Pressing the *Rev* (reverse) button causes the current to flow from *L1*, through the overload contacts *T1* through coil *C*, terminal *C3* on the contactor, across the crosshatch line of the reversing switch, which is closed by pushing a push button, through the unshaded contacts of the forward push button, through the stop button to contact *C5* and to terminal *L2* of the line. Current flowing through coil *C* causes the plunger of the coil to move the four contacts attached to the crosshatch rod to the left. The crosshatching represents insulation. When the *Rev.* contactors close, current flows from *L1* to the left-hand contact of the reversing contactor to terminal *T3*, through the motor terminal *1* to *3*, terminal *T2*, across the contactor to terminal *T6*, through the condenser terminal *1* to *4* to terminal *T5*, across the reversing contactor to terminal *L2* of the line. There is also a flow of current from *L1* through overload coil *T1* to terminal *2* of the motor, through the winding to terminal *4*, through the overload coil *T4* to terminal on the reversing contactor and to line *L2*. Thus the direction of the flow of current through the motor winding *3* and *1* is reversed, causing the direction of rotation of the motor to be reversed.

When limit switches are used the lines marked *B* and *C* are removed and the dotted lines substituted. The purpose of the limit switch is to open the circuit when the machine operated by the motor has reached the limit of its movement or travel.

is ¾ horsepower, 110 and 220 volts. They can be operated on any frequency from 0 to 60 cycles. Inherently these motors are high-speed motors and have series motor characteristics, that is, the speed changes with the load—the greater the load, the slower the speed. Universal motors respond to speed regulation by resistance, which makes them especially valuable for driving loads such as sewing machines, bookkeeping machines, fans, etc. The output of these motors

Fig. 8. Foot-operated Controller for Small Motors

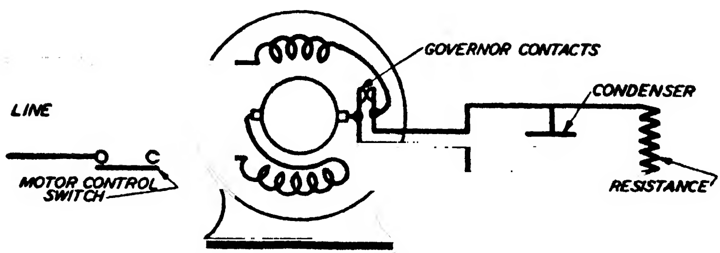


Fig. 9. Diagram of Governor Control Which Inserts Resistance in a Series Motor Circuit When Speed Becomes Too Great. When Speed Is Below Normal the Resistance Is Short-circuited by Closing of the Governor Contacts

is less on alternating current than on direct current, and this has to be considered in their control, mainly where they are used for their universal characteristic. On direct current a step of resistance may become necessary to get correct operation.

The universal motor is inherently not reversible, and good commutation can be obtained only in one direction; also the power output is less in the reverse direction, therefore reversing should be limited to infrequent service and short-duty cycle. For the control of these motors, plain snap switches can be used. Fig. 8 shows a foot-operated sewing machine controller.

Where constant speed is required for a universal motor drive, independent of load changes, governors have been developed which act

on the principle of a centrifugal switch, introducing a resistance when the motor speeds up and short circuiting the resistance when normal speed is restored. The connection is shown in Fig. 9. Often a condenser is connected across the switch points to protect them from undue arcing.

Repulsion-Induction Motors. As the name indicates, the motor starts as a repulsion motor and runs as an induction motor. This type of motor is commonly referred to as an "RI" motor and is perhaps the most widely used single-phase motor. It finds its application in refrigeration machinery, compressors, pumps, fans, etc. The inrush current is from 300 to 350 per cent of normal full-load current, and has high starting efficiency, that is, torque per ampere inrush current.

The motor starts as a repulsion motor, but on reaching a predetermined speed the governor operates due to the centrifugal force, changing it to an induction motor. The movement of the governor pushes the short-circuiting device forward and short-circuits the commutator bars and also lifts the brushes. This results in a short-circuited armature and frees the brushes from friction, the motor becoming in effect an induction motor with a squirrel-cage rotor. The commutator is in service only during starting and provides the continuously rotating field by commutation to produce the torque during starting.

It can be seen readily that the actual starting cycle of the repulsion-induction motor is entirely automatic and that no outside starting equipment is necessary, except the means of connecting the motor to the line and disconnecting the same.

As mentioned previously, this type of single-phase motor is perhaps the most widely used motor and is being built up to 15 horsepower capacity. They are in nearly all cases double voltage motors, that is, the motors can be used in either 110 or 220 volts. Four leads are brought out, permitting the stator windings to be connected either in parallel for 110 volts or in series for 220 volts. Fig. 10 shows the electrical connection necessary for the different voltages.

Since these motors can be used on 110 and 220 volts without reconnection inside the motor, and because often the voltage to which they are to be connected is not known, it is sometimes an advantage

that the overload protection which may be supplied with the starting equipment can also be used on both voltages.

Fig. 11 shows a method by which this can be accomplished. It will be noted that the overload device OL is connected in only

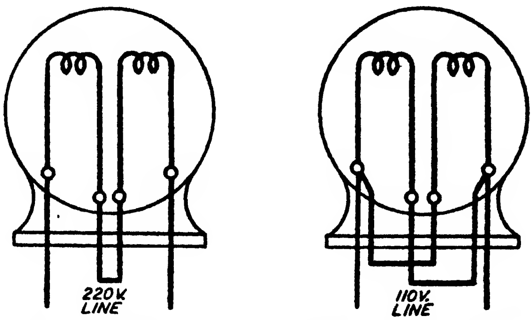


Fig. 10. Diagram Showing How 110/220 Volt Motors Can Be Connected to Operate on Either Voltage Supply Line

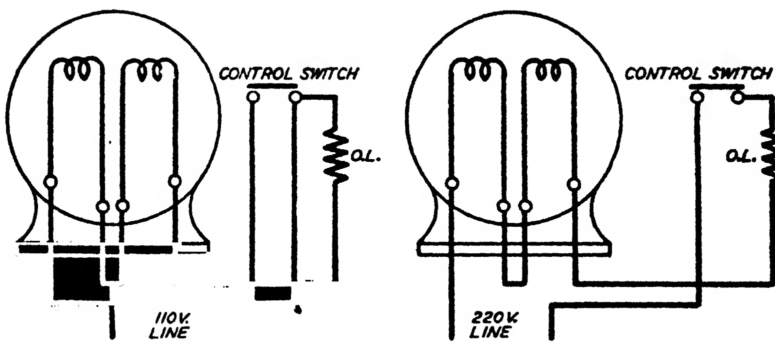


Fig. 11. Diagram Showing How the Control Switch and Overload Devices Are Connected on 110/220 Volt Single-Phase Motors

one winding on 110 volts. This may be considered a weakness of this arrangement, since in case the other winding should break down, the motor will not be protected. Therefore, if the motor is connected to a definite voltage, connecting the overload in series with both windings and changing the heater element is the better practice.

Manual Across-the-Line Starter. Where no-voltage release is not required, the simplest form of starting device would be a common snap switch which has a horsepower rating. For a manual starting device where overload protection is to be provided, an auxiliary breaker, Fig. 5, which has a maximum rating of 1 horsepower,

110/220 volts, can be used. For larger motors, manual starters, Fig. 12, are suitable.

These starters are being built in two sizes. Size 0 has a rating

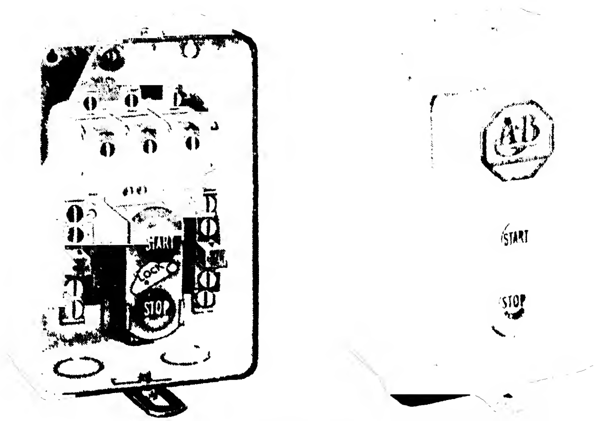


Fig 12 A Manually Operated Starter for Single-Phase Motors

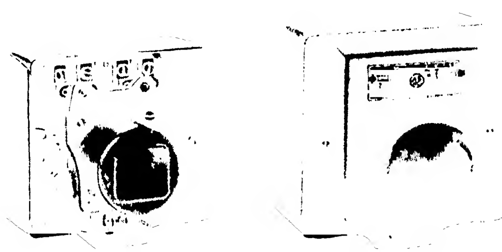


Fig 13 A Pressure-operated Control Switch

of 1 horsepower, 110 volts and $1\frac{1}{2}$ horsepower, 220 volts. Size 1 has a rating of $1\frac{1}{2}$ horsepower, 110 volts and 3 horsepower, 220 volts.

Switches. Where single-phase motors are to be automatically controlled, pressure switches, float switches, and thermostats can be used. Fig 13 shows a two-pole pressure switch, which can be used on either air or water. The operation of the switch depends on the pressure of the water, which acts against a diaphragm that is backed up by a spring. The tension on this spring determines how high the motor has to pump the pressure before sufficient motion on the diaphragm is obtained to throw the pressure switch contacts to the "Off" position. When pressure falls, the spring pushes the diaphragm in the opposite direction, closing the contact.

Pressure switches are also used in connection with refrigeration equipment to control the low pressure and the high pressure of the system. The low pressure controls the amount of refrigeration and has to be adjustable as to range and differential, that is, controlling the cut-in and cut-out point of the pressure switch. The high-pressure switch is a safety device, preventing too high a pressure, which would endanger the refrigeration system. These pressure switches make use of metal bellows to prevent the possibility of leaks in the system.

Fig. 14 shows a conventional float type switch. The operation

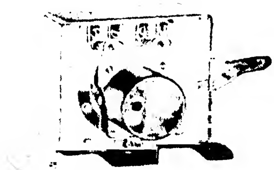


Fig. 14. A Float-operated Control Switch

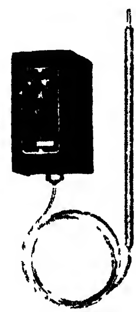


Fig. 15. A Thermostat-operated Control Switch

of this device depends on the change of the water level in tanks or standpipes. A float is used which is counterbalanced by a weight and furnishes the power required for the switch operation.

The switching can be arranged for either tank or sump control, that is, the pump is started either on a falling water level or a rising one.

Thermostats. Fig. 15 shows a thermostat which is used to start motors that control fans in air-conditioning and heating installations. They may also be used to start circulating pumps and refrigeration compressors. The functioning of these devices depends on the expansion and contraction of gases or volatile liquids under temperature changes.

A metal bellows system, which is filled and sealed with a liquid or gas, consists of a bellows (enclosed in case), a coiled capillary tube and a bulb, Fig. 15. The expansion of the gas or liquid inflates the

bellows, exerting pressure against a spring, and the motion obtained is used to operate the switch. The cut-in and cut-out points are adjusted by changing the spring tension. For smaller motors these devices are used to open and close the motor circuit; for larger motors they serve as pilot switches or relays controlling automatic starters.

Automatic Across-the-Line Starter. Fig. 16 shows an automatic across-the-line starter for single-phase motors. It consists of a magnetic switch and an overload relay When the coil is

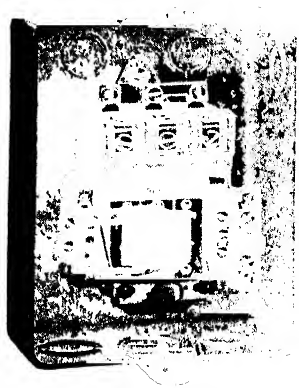


Fig 16 A Single-Phase Automatic Across-the-Line Starter

energized by the pilot device, the armature of the magnet is attracted, closing the switch contacts and starting the motor. The overload relay contacts are in series with the operating coil. In case of an overload, the contacts will open, de-energizing the coil, and the switch will drop open, disconnecting the motor.

These starters can also be operated by a "Start" and "Stop" push button. This method of control usually is referred to as three-wire control. When the "Start" button is pressed, the switch coil is energized and the switch closes, connecting the motor to the line and also closing an auxiliary switch which connects the operating coil directly to the line. This holding circuit is connected over the overload relay contact and the stop button. Opening of either one de-energizes the holding coil and opens the switch. The switch cannot close again unless the "Start" button is operated. This opera-

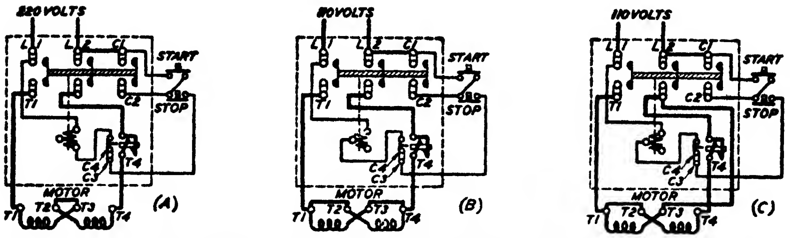


Fig. 17 Connection Diagram of a Single-Phase Across-the-Line Automatic Starter for a 110/220 Volt Motor

On 220 volts *(A)* the full number of turns on a contactor coil are used, while on 110 volts *(B)*, one-half the turns are used A wiring arrangement which makes possible using the same thermal element of overload relay *T4* for motors connected to either 110 or 220 volts is shown at *(C)*. This requires an extra line between the motor terminal *T3* and the starter terminal

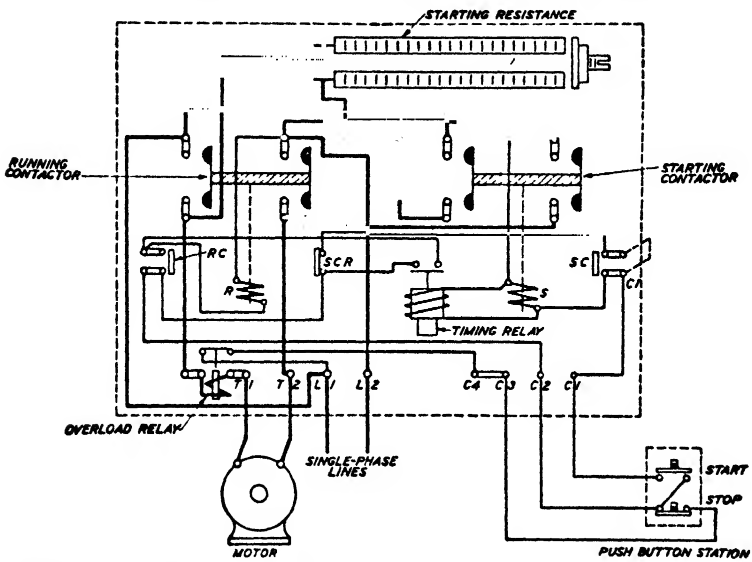


Fig. 18. Controller Diagram of a Two-Point Starter Which Connects Resistance in Series with the Motor Line When Starting

When the start push button Fig 18 is pressed current flows from *L1* through the overload trip contact, link *C4-C3*, across the stop button and the diagonal line to the start button, across that button to terminal *C1* and link *C1* to the starting contactor coil *S*, to the upper right-hand terminal of the starting contactor, to line *L2* As soon as the starting contactor closes, the reactance of the starter contactor coil applies full voltage across the timing relay, which has a dash-pot and gives a certain time interval before its plunger moves up and closes the contacts directly above it. When the timing relay closes the contacts, current flows from *L1* through the stop button, terminal *C2*, through timing relay contacts, through the running contactor coil *R* and to line *L2*. This closes the running contactor connecting *L1* through the contactor to motor terminals *T1* and *T2* to line terminal *L2*.

When the starting contactor closes, the contact *SC* is also closed, thus providing a holding circuit through the stop button, *C2* and coil *S*, to line *L2*, when the start button is released. When the running contactor closes, it also closes the control contact *RC* which gives a circuit for holding the running contactor closed. At the same time the running contactor opens the contacts *SCR*, stopping the flow of current through the starting coil *S*. Then the starting contactor opens and in doing so it opens the control contact *SC*.

A two-wire control for starting the motor, in addition to the push button station, can be connected as shown by the dotted lines at *C1* near the *SC* contacts.

tion is spoken of as "No voltage protection" Fig 17 describes the connection of a single-phase across-the-line automatic starter.

Reduced Voltage Starter The starting devices so far mentioned are for single-phase motors, which can be thrown directly across the line Power companies' restrictions, however, may limit the permissible starting current, in which case a step of resistance becomes necessary.

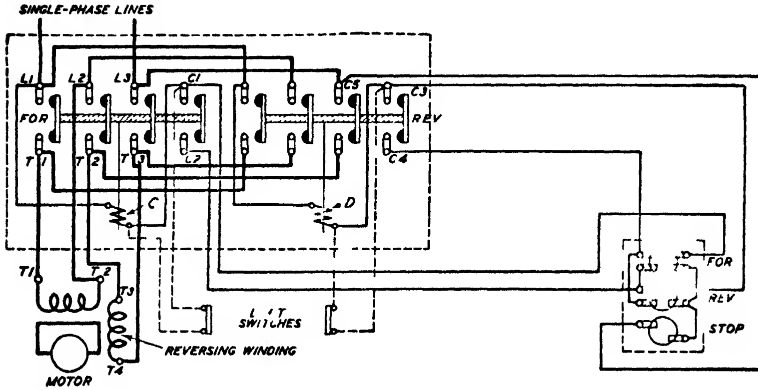


Fig 19 Controller Connection Diagram for a Reversing Type Repulsion Start Induction-Run Single Phase Motor

Pushing the start button marked *For* causes current to flow from *L1* to the contactor coil *C* to *C1* through the forward push button shaded contacts through the reversing and stop push buttons terminal *C5* to line *L3* This closes the forward contactor joining *L1* to *T1* and allows the current to go through the main winding *T1* to *T2* to terminal *T2* across the contactor to *L2* and reversing winding lead marked *T3* through the winding to *T4* terminal *T3* of the contactor and to line *L3* The upper terminals of the contactor are marked *L1* *L2* and *L3* because a standard three phase contactor is used The control contacts *C1* and *C2* are joined together when the contactor closes and provide a flow of current through the contactor coil *C* which holds the contactor closed until the stop push button is pressed

When it is desired to reverse the direction of rotation of the motor (which is running) the stop button is pressed and after the forward contactor opens the Rev (reversing) push button can be pressed Pressing the reversing button causes the reversing contactor to close joins line *L1* to terminal *T1* of the motor allowing current to flow through it to upper terminal *L2* and the reversing contactor to terminal *T4* of the reversing winding through that winding to *T3* terminal *T2* across the contactor to terminal *C3* and line terminal *L3* The flow of current through the reversing winding is opposite to the direction of flow with forward contactor closed and the motor runs in the reverse direction When limit switches are used connect as shown by dotted lines and remove lines from coil *C* to *C1* and coil *D* to *C3*

Fig. 18 describes a two-point starter. Closing of the starting switch connects the motor through a step of resistance. A timing device is put into the motor which will, after a predetermined time, close the second switch, which shorts out the resistance and connects motor to full-line voltage.

Repulsion-induction motors can also be used for reversing service. Fig. 19 describes the method of connection for a four-lead motor.

POLYPHASE MOTOR STARTERS

Squirrel-Cage Motors. In the foregoing we have given consideration to the single-phase motor and its control requirements, which are varied but quite simple, since mostly small motors having only starting and stopping requirements are to be considered.

In the case of polyphase motors—principally the squirrel-cage

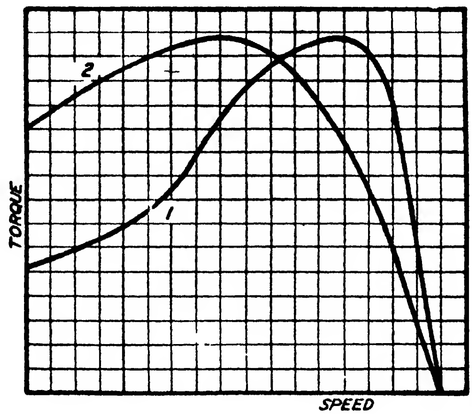


Fig. 20. Torque Speed Curves for (1) Standard Type Squirrel-Cage Motor and (2) Low Current Inrush or High-Torque Squirrel-Cage Induction Motor

The torque in an induction motor when it is operated at synchronous speed is zero, or at the base line of the extreme right-hand part of the curve. As the speed of the motor falls below synchronous speed the torque increases. The height of the curves *(1)* and *(2)*, at the left above the horizontal line marked "Speed" indicates the torque or turning effort exerted by the motor when the switch is first closed. Thus the torque *(2)* produced by the high-torque squirrel-cage motors is nearly twice that of the standard squirrel-cage induction motor. This enables the high-torque motors to start the motor and machinery from rest with less line current than a standard type motor uses. Likewise when operating at full load and a heavy overload occurs the motor will decrease a greater amount in speed and also produce more torque to keep the machine moving than will the standard squirrel-cage motor.

motor—matters are different, and control equipments are of great importance in order that the motor may function properly in regard to load requirements.

In order that the proper motor and control be selected, it is necessary to consider:

(1) The motor characteristic in relation to the load.

(2) The design, construction, starting requirements of the machine, and the duty cycle to be obtained.

(3) The power supply and the effect of the motor on the same.

In order that the starting requirements for a squirrel-cage motor may be fully understood, it is advisable to mention the general

characteristics of this type of motor. The inrush current, that is, the current which flows when motor is at a standstill and is connected to full-line voltage, is high, varying from five to eight times the full-load motor current. This current depends on the resistance of the rotor, and the efficiency varies with the rotor resistance, that is, the lower the rotor resistance, the higher the inrush current and the

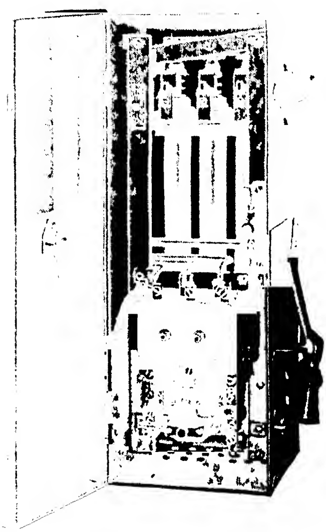


Fig. 21 Manually Operated Resistance Type Starter for Polyphase Motors

higher the efficiency. With high rotor resistance a lower inrush current is obtained, and efficiency is correspondingly lower.

Motors which have a current inrush of three to three and one-half times normal full-load current are ordinarily called low-current inrush or high-torque motors. Motors having five times current inrush when starting are called "line start" motors. Motors which have six times current inrush are called standard squirrel-cage motors. Motors which take more than six times current inrush are called low-resistance squirrel-cage motors.

Fig. 20 shows general torque speed curves of (1) standard type and (2) low inrush or high-torque squirrel-cage motors.

The starting inrush current may be lowered by reducing the voltage across the motor; however, the starting torque varies with the square of the voltage. This is important to remember when

squirrel-cage motors are being started by reduced voltage starters. It is possible to reduce the voltage across the motor terminals by inserting resistance in the line and also by using a transformer. With the same voltage across the motor terminals, the current from the line is higher when a resistance type starter is used; with a transformer type starter the current is lower. This is an important point to remember if power supply is limited. When power supply is limited, it may be advisable to use a transformer type starter, since the current taken from the line to start the load is smaller. However, the voltage disturbance will be greater and more sudden. If power lines are also carrying lighting loads, then a resistance type starter of either the step-by-step or the gradual type should be used. Gradual resistance type starters are of the compression type as shown in Fig. 21.

In the selection of the motor, we will have to consider the efficiency of the drive. It will not always be possible, however, to select a motor of the highest efficiency. In many cases other considerations are of more importance. For instance, a slip-ring motor with speed regulation may be more economical to use than a single-speed motor, even though the drive is less efficient from an electrical standpoint, if by means of the speed regulation more and better production is obtained.

An oversize motor, even though it has higher efficiency, will be uneconomical, if selected only to get sufficient starting torque. In case of group drives, a large motor will be uneconomical if all driven machines are not fully loaded. It may, however, be the best to use if installation cost, or reliability is of prime importance. From these examples it can be seen easily that it is necessary to study each application in order to arrive at the best selection of the motor and its control.

For any motor application the starting cycle is of prime importance, especially in case of a squirrel-cage motor, since selection of the proper control equipment depends on it. After all, it should be realized that the control is the binding element between the driven machine and the motor and insures that the power is properly applied to the machine, giving it full function.

In the selection of the control, consideration has to be given to how much responsibility shall be assumed by the machine operator

for proper operation. This factor will determine if control shall be manual, semiautomatic, or full automatic.

If manual control is selected, all basic operations of the control, such as throwing in levers and closing switches, will be performed by hand. If automatic control is selected, the functions will be through the operation of push buttons or master switches.

In general, if the function of the control apparatus is to start a motor which runs in one direction, the control is called a motor starter. Control apparatus used for other purposes, such as reversing, plugging, speed changing, and slowing down is referred to as a motor controller.

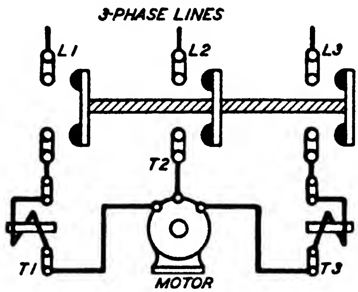


Fig 22 Diagram for Manual Type Across-the-Line Three-Phase Starter

The same type of starter is used for single-phase induction motors, and terminals *L2* and *T2* are not used. This type can also be used on two-phase three-wire motors, in which terminals *L2* and *T2* are the common wires to both phases. If the motor is a two-phase four-lead motor, one lead of each phase is joined to terminal *T2*.

Manual Across-the-Line Starters. The simplest form of squirrel-cage motor starter is the manual starter shown in Fig. 12, where the motor is started by connecting it directly across the line. Besides starting the motor, overload protection for constant-speed motors is obtained by thermal overload devices. This starter does not provide "no-voltage protection," but this is not required with some driven machines such as fans, blowers, pumps, etc. These starters can be operated by means of buttons, as shown in Fig. 12, or by means of a hand lever. They are provided with two overload trips and, in case of an overload, they open the switch. In order to reset the overloads, the starter operating mechanism has to be brought into the "Off" position. This feature has to be incorporated so that it is impossible to hold the starter closed in case of an overload.

Fig. 22 presents the connection diagram for this type of starter. The maximum horsepower for which these starters are built is 5 horsepower, 220 volts and 7½ horsepower, 440/550 volts.

Reduced Voltage—Resistance Method. In case starting current

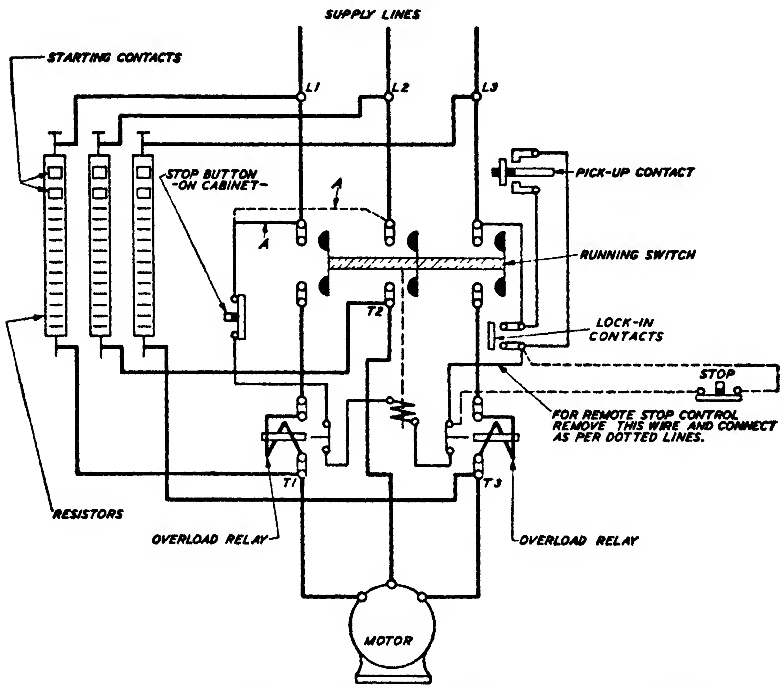


Fig. 23. Connection Diagram of a Motor Starter Using Manual Lever to Close the Starting Contact

Final movement of the operating handle closes the pick-up contact This establishes an electrical circuit from line *L1* through the stop button on the cabinet to the overload trip contact *T1* to *T3*, through the remote stop button across the pick-up unit to line *L3* Current flowing through the contactor coil connects the supply lines through the contactor directly to the three-phase motor The closing of the contactor closes the lock-in contacts so that the handle of the motor starter can be returned to the "Off" position and the running switch will stay closed. Should an excessive current flow through either of the lines *T1* or *T3*, the overload contact is opened and the motor is shut down the same as when the stop buttons are pressed On two-phase, three-wire lines, *L2* and *T2* are the common wires to each phase of line and motor. Then the control wire "*A*" must be connected as shown by the dotted line to the common line *L2*.

of the motor has to be limited because of power companies' limitations, or to protect the driven machine, or to prevent belt slippage, a starter which limits the current must be employed. Fig. 21 shows such a starter, which is of the compression resistance type, as previously mentioned. Lifting the operating handle into the horizontal

position connects the motor to the line through the resistance. Further motion compresses the resistance, thus increasing the current through the motor. The last motion connects the motor to full-line voltage. The operating handle is then returned to the "Off" position. The electrical connections are described in Fig. 23.

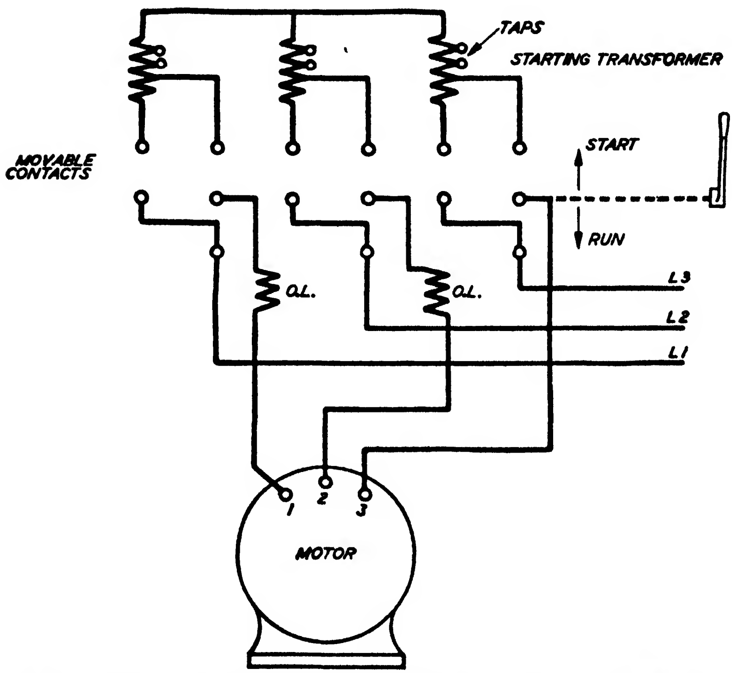


Fig. 24. Manual Type Starting Switch, Using Starting Transformer, Which Is Often Called "Starting Compensator"

Moving the handle of the compensator to the start position moves the center row of contacts to the upper row. This connects the lines *L1*, *L2*, and *L3* to the autotransformer. Reduced voltage is obtained from the taps on the autotransformer to the motor. Moving the lever to the running position connects the movable contact directly to the line. The handle is held in the running position by a trigger catch, which can be released by the overload relay *(OL)* when the current to the motor exceeds the proper amount.

Transformer Method. The transformer type of reduced voltage starter is commonly called "Compensator." In operating this type of starter, the operating handle is first thrown into the "Start" position. This connects the motor through the autotransformer to the line at reduced voltage, which, in turn, reduces the starting current. When the motor has attained sufficient speed, the handle is thrown into the running position. This operation disconnects the

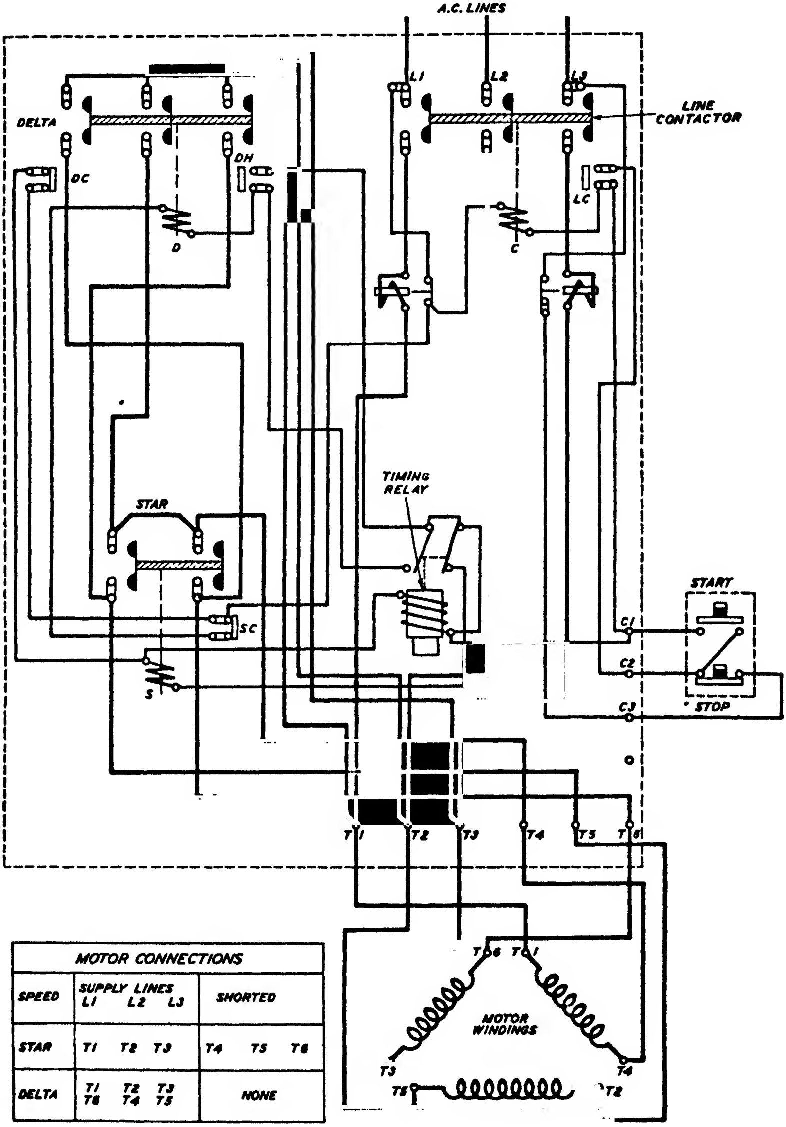
motor from the autotransformer and then connects it directly across the line, Fig. 24. Throwing the handle from the "Start" into the "Run" position has to be done quickly in order to prevent a heavy current inrush. A mechanical locking arrangement which forces the operator to throw the handle into the "Start" position first, then quickly into the "Run" position, is often used.

An autotransformer starter causes two distinct current inrushes, (1) when motor is first connected to the circuit and (2) when motor is disconnected from the transformer and connected to the full-line voltage. Power companies, therefore, are likely to prohibit the use of transformer type starters on their distribution lines which carry lighting loads. Resistance type starters do not offer these objectionable features. Autotransformer starters are provided with taps of 50, 65, and 80 per cent of line voltage.

Star-Delta Method. There is one other method of reduced voltage starting of squirrel-cage motors, namely, the Star-Delta connection. Motors employing this method have to be designed for it originally by bringing out six leads. It is little used in America and most requirements are for machines shipped to Europe, where this method is still employed. It can be applied only where the starting torque is low, since only 33 per cent of full-load torque is obtained at starting. Fig. 25 describes the connection on an automatic Star-Delta starter.

Automatic Across-the-Line Starter. The simplest form of automatic squirrel-cage motor starter, is the across-the-line starter, and, as the name implies, the motor is connected directly to full voltage. These starters are built up to 300 horsepower, 220 volts and 600 horsepower, 440/550 volts. Naturally the large sizes can be used only where sufficient power supply exists, such as will be found in the auto, chemical, and steel industries. These starters are simply magnetic contactors with overload protective devices, mounted in suitable enclosing cases and actuated from one or more start and stop push button stations. Such an across-the-line starter is illustrated in Fig. 26. Pressing the start button causes the contactor to close and establishes a holding circuit by which the switch is retained closed after pressure on the start button has been released.

Fig. 27 presents the diagram of connection for a three-phase and two-phase four-wire starter. Where the inrush current is limited



MOTOR CONNECTIONS		
SPEED	SUPPLY LINES L1 L2 L3	SHORTED
STAR	T1 T2 T3	T4 T5 T6
DELTA	T1 T2 T3 T6 T4 T5	NONE

Fig. 25. Connection Diagram of an Automatic Star-Delta Starter

Pressing the start button allows current to flow from *L1*, through the overload trip contact and line contactor coil *C* to *C1*, across the start button and through the stop button to *C3* and the other side of the line *L3*. This closes the line contactor joining the main line *L1*, *L2*, and *L3* to the corresponding terminals *T1*, *T2*, and *T3* of the motor. Also the lock-in contact *LC* connects the line contactor coil through *C2* to the stop button, thus holding the line contactors closed when the start button is released. At the same time that the current flows through the line contactor, coil *C*, there is a flow of current from line *L1* through the interlock contacts

owing to power companies' regulation or for protection of the driven machine, a step of resistance is employed Such a starter consists of two magnetic switches, one of which connects the motor to the line through the resistance when the start button is pressed A tim-

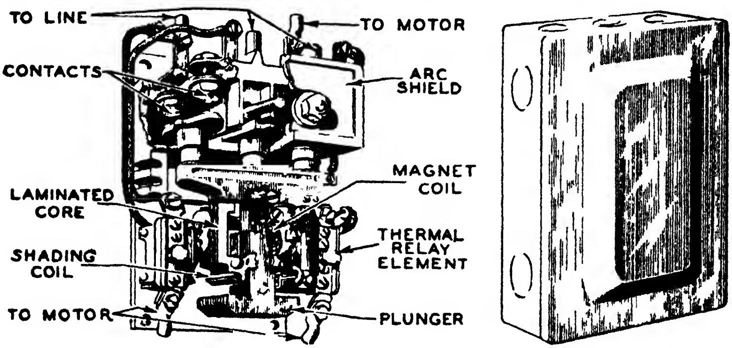


Fig 26 Interior and Exterior Views of a Solenoid-Operated Across-the-Line Starting Switch

ing device is then put into operation which energizes the second contactor connecting the motor to full-line voltage

Reduced Voltage Automatic Starter Fig 28 shows such a single-step resistance starter These starters are also referred to as two-point starters first point when motor is connected to the line with the resistance in series, second point when the resistance is shorted out

Fig 29 presents the diagram of connection Automatically

SC and *DC* through the star contactor coil *S* timing relay switch to *C1* through the start and stop button to *L3* There is also a flow of current from the upper terminal of the star contactor coil to the upper terminal of the timing relay coil This causes the star contactor to close joining motor leads *T4*, *T5* and *T6* This allows the motor to start with the motor winding connected in Star or Y In this connection each phase winding of the motor such as *T1* and *T4*, receives about 58 per cent of the line voltage between line wires *L1* *L2* or *L3* When the star contactor closes it opens the interlock *SC* so that there is no circuit through the coil *D* of the delta contactor

Current flowing through the timing relay coil will swing the hinged contacts from the right to the left thus opening the circuit through the star contactor coil *S* This allows the star contactor and interlock to return to the position shown in the diagram thus opening the motor leads *T4* *T5* and *T6* Likewise the interlock below the star contactor is closed the timing relay has made connection and a complete circuit is established through the delta contactor, coil *D* The flow of current is from line *L1* through the interlock *SC* below the star contactor the delta contactor coil *D* and lower terminal of the interlock *DH* through the left-hand blade of the timing relay to *C1* through the lock in contacts *IC* which are now closed, terminal *C2* through the stop button to *C3* and line *L3* When the delta contactor closes the interlock *DC* opens and holding contacts *DH* close This interlock *DC* prevents current flowing through the star contactor coil and opens the circuit through the timing relay coil allowing the relay to return the upper contacts to the position shown in the diagram The delta contactor is held closed by the right-hand interlock *DH*

The closing of the delta contactor connects motor lead *T6* to *T1* also *T4* to *T2* and *T5* to *T3* This connects the motor windings in delta Then the motor windings receive full-line voltage.

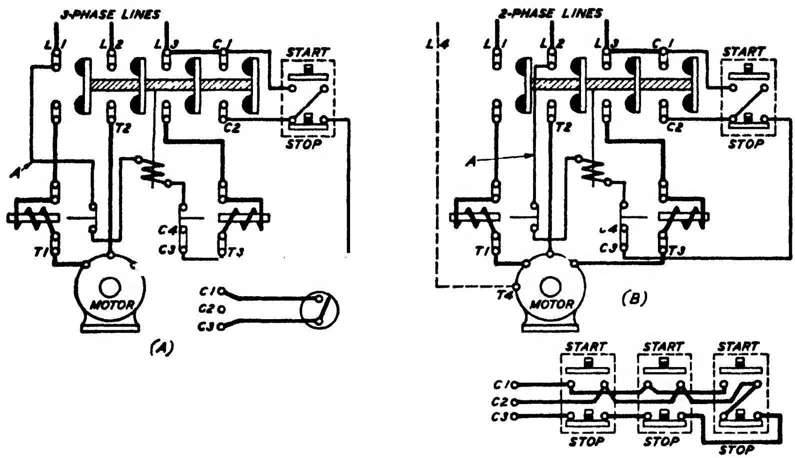


Fig. 27. Connection Diagram for a Three-Phase and Two-Phase Four-Wire Motor Starter, Which Connects the Motor Directly Across the Line

For a single-phase across-the-line automatic starter omit line wires and motor leads *L2* and *T2* For a two-phase three-wire system omit line *L4* and join motor lead *T4* to terminal *T2* Line *L2* is the common lead in a two-phase three-wire system *T1* and *T4* is one phase of the motor and *T2* and *T3* the other phase

Instead of push button switches a two-wire control device, such as a thermostat, float switch, or pressure switch indicated at *(A)*, is connected to terminals *C1* and *C3* No connection is made to terminal *C2*

When it is desired to use two or more push buttons the connection to these buttons is shown in the bottom part at *(B)* The three terminals, *C1*, *C2* and *C3* are joined to the correspondingly numbered terminals to which the first push button is connected

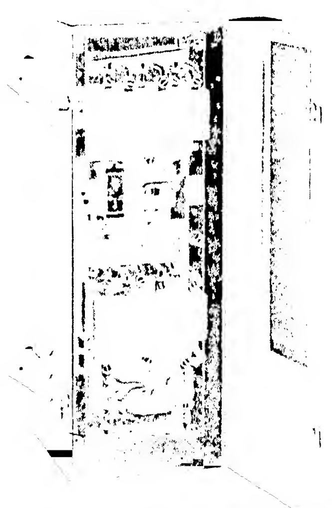


Fig. 28 Single-Step Resistance Starter

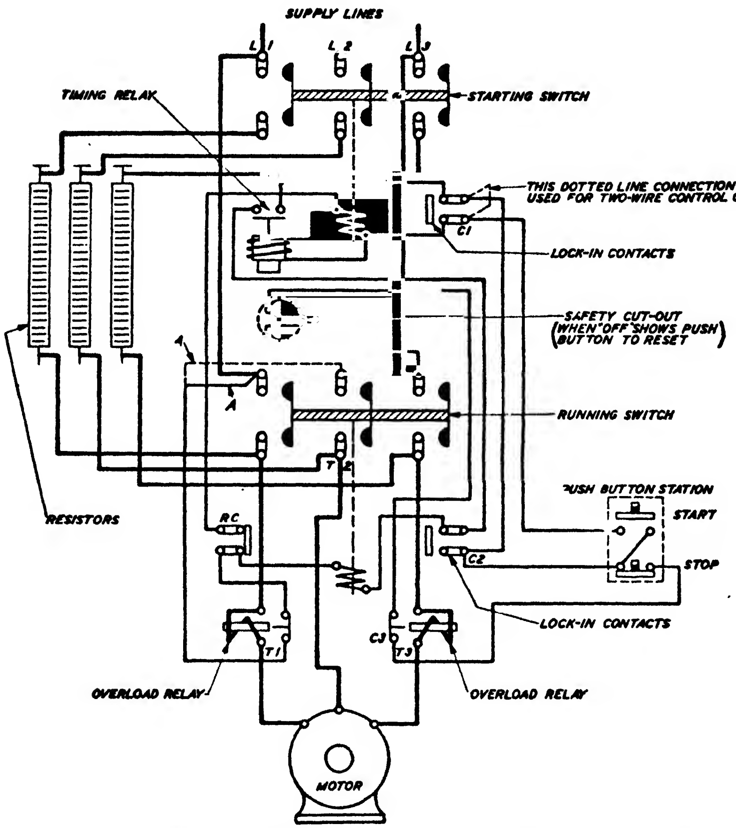


Fig. 29. Diagram of One-Step Resistance Starter with Squirrel-Cage Motor (Automatic Starter)

Pressing the push button marked "Start" causes current to flow from line *L1*, through line *A*, to the overload relay contact *T1*, across the running switch interlock *RC* to the upper terminal of the starting switch contactor coil. Here it flows through both the timing relay and starting switch contactor coil to *C1*, through the start and stop button, overload relay contact *C3*, through the safety cut-out to line *L3*. This closes the starting switch contactor, allowing current to flow through the resistors and overload relays *T1* and *T3* to the motor. When the starting switch contactor operates, the lock-in contacts *C1* are joined, thus holding the circuit of the starting switch contactor coil through the stop button so the start push button can be released. After a certain delay interval the timing relay operates, joining the two contacts. This provides a flow of current from *L1*, wire *A*, through the overload relay contact *T1*, through the running switch contactor coil, to the timing relay contact, then contact *C2* to the stop button, contact *C3* and line *L3*. Current flowing through the running switch contactor coil closes the running switch, connecting *L1*, *L2*, and *L3* directly to the motor terminals *T1*, *T2*, and *T3* without any resistance in the circuit. At the same time the lock-in contact *RC* opens and *C2* closes, connecting the running switch contactor coil directly to the stop button and the other side of the line. The opening of the lock-in contactor *RC* interrupts the flow of current through the starting switch contactor coil and timing relay, allowing them to return to the "Off" position. The opening of the starting switch opens the lock-in contactor *C1*.

operated transformer-type starters operate on the same principle as described in connection with manual compensators, except that

the closing of the starting and running circuits is performed by magnetic switches upon operation of the start button. Fig. 30 shows an automatic transformer type starter for low-voltage motors.

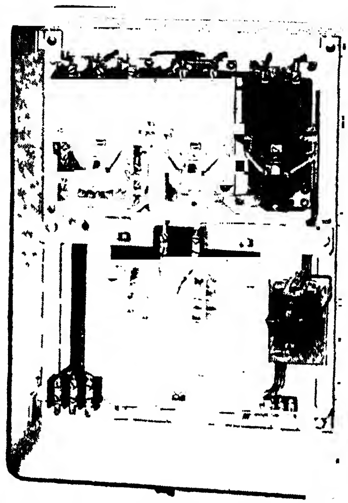


Fig. 30 Automatic Transformer Type Starter

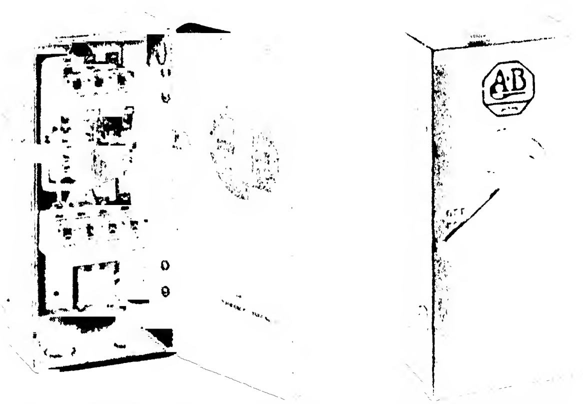


Fig. 31. An Across-the-Line Starter with a Plain Disconnect Switch

Starters for Special Conditions. For simpler and often better installation, across-the-line starters are combined with fused or unfused disconnect switches and also with circuit breakers. These starters are known as combination starters. Fig. 31 shows such a starter having a plain disconnect switch.

Fig. 32 shows a starter with line switch and fuses, and Fig. 33 an across-the-line starter with circuit breaker. Fig. 34, shows the outside view of a water-tight combination starter.

Modern starters use front-operating handles for the operation

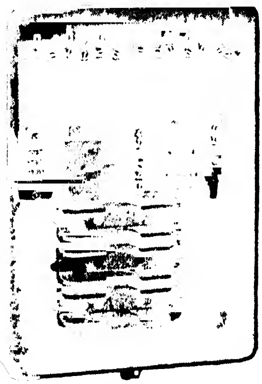


Fig. 32 Solenoid-operated Starter with Line Switch and Fuses

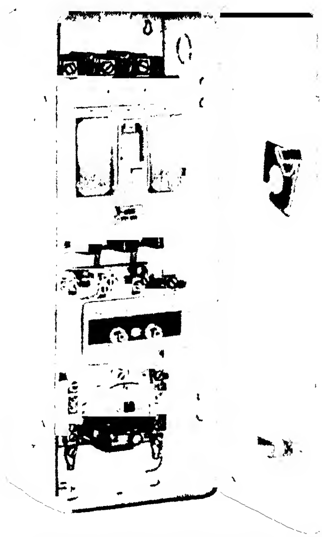


Fig. 33 Across-the-Line Starter with Circuit Breaker

Fig. 34 Water-tight Combination Starter

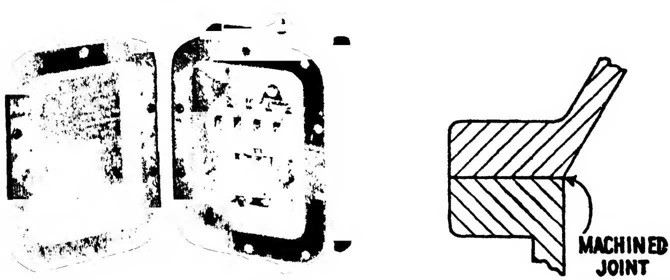


Fig. 35 Air Break Explosion-proof Across-the-Line Starter

of the disconnect switch. Across-the-line starters and combination starters are mounted in different types of enclosures such as dust-tight, water-tight and explosion-proof types, depending upon conditions of installation.

Fig. 35 shows an air break explosion-proof across-the-line starter. A heavy cast-iron enclosure is used to withstand the pressure in case of an internal gas explosion. Machined joints are provided between box and cover so that burning gases cannot escape from the enclosure.

For certain industries it is necessary to use oil-immersed switching equipment in order to prevent the effect of corrosive gases on the starter mechanism. Fig. 36 shows such an oil-immersed starter. In order to inspect the starter the oil tank has to be lowered.

Fig 36 Oil-immersed Starter

Across-the-line squirrel-cage motor starters are also used in connection with high voltage motors up to 4,800 volts. An oil-immersed switch is used to connect the motor to the line and current transformers are provided for the overload relays. The oil-immersed switch is operated by a magnet. Since the coil current is rather high, an operating relay is used, so that the push button and overload relay contacts need to handle only the small relay coil current. This feature is also employed in low-tension control where larger size magnetic switches are involved.

Fig. 37 shows a high tension across-the-line motor starter.

Some machines, such as washing machines, machine tools, and bending rolls require reversing. This can be accomplished electrically by reversing two lines to the motor. Fig. 38 presents the diagram of connection of an across-the-line reversing starter. A three-button station marked "For." (forward), "Rev." (reverse), and "Stop" is used for the operation. Pressing the "Forward" button connects the motor in one direction; pressing the "Reverse"

button reverses two lines and causes the motor to operate in the opposite direction. Operating the "Stop" button brings the motor to a stop.

Fig. 39 shows such an across-the-line reversing switch. The switches are mechanically interlocked, so that only one switch can close at one time.

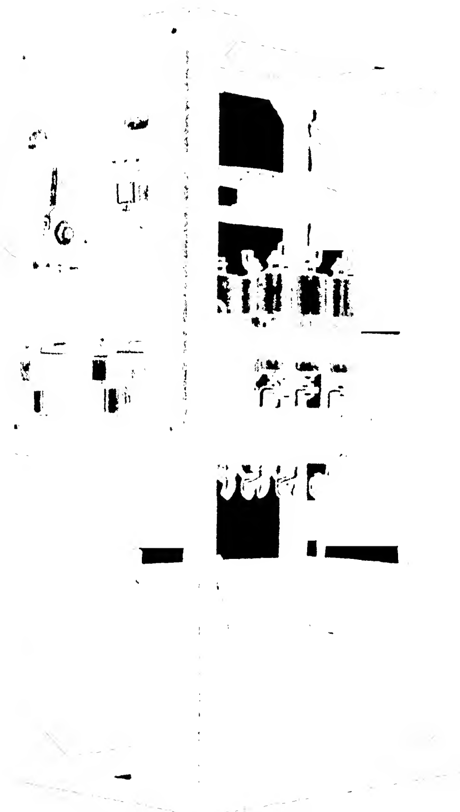


Fig 37. High-Tension Across-the-Line Starter

A reversing switch is also used to bring a machine to a quick stop by "plugging" the motor. In that case the reverse button control circuit is so arranged that the magnetic switch will drop out as soon as the button is released. This feature is used in connection with machine tools. Reversing switches are provided in different types of enclosures and, at times, combined with line disconnect switches.

Magnetic controllers consist of an assembly of magnetic switches and relays, for establishing proper sequence for machine operation, which have a number of motors driving the different motions.

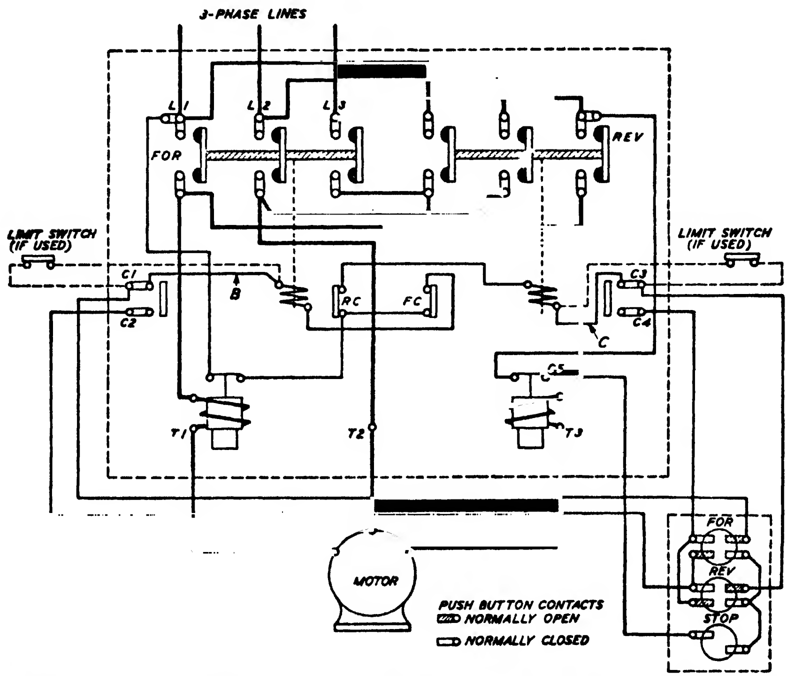


Fig. 38. Connection Diagram for an Across-the-Line Reversing Starter for a Three-Phase Squirrel-Cage Motor

Pressing the *For.* (forward) button causes a flow of current from *L1* through contacts of overload relay *T1*, reverse control interlock contact *RC*, through forward control interlock *FC*, through the forward contactor coil, wire *B*, to terminal *C1*, through forward, reverse, and stop push buttons, overload relay contact *C5* to line *L3* This closes the forward contactor, allowing current to flow from the three-phase line into the motor When the forward contactor closes, the interlock *C1-C2* closes and the reverse control interlock *RC* opens so that the reversing switch cannot close until the forward contactor opens. When it is desired to reverse the motor, pressing the stop button will return the forward contactor and interlock to the position shown. Then the reversing button can be pressed and current will flow from line *L1*, through overload contact *T1*, through interlock *RC*, through reversing contactor coil, wire *C*, through the reversing, forward, and stop push buttons, overload contacts *C5* to the other side of the line. This closes the reversing contactor, which at the same time closes the interlocks, *C3* and *C4*, so that the reversing push button can be released and the contactor held closed Also the interlock on the forward contactor control circuit *FC* is opened.

Fig. 40 shows a controller for a machine tool. These controllers are operated by push buttons or master switches and limit switches. Timing relays have often to be employed to complete the cycle of operation. They may be arranged to go through one cycle when the

"Start" button is pressed, or they may go through repeated cycles once the "Start" button is operated. Reversing, plugging, and positioning cycles may be incorporated where required.

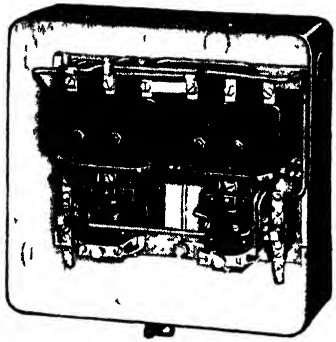


Fig 39 Across-the-Line Reversing Switch

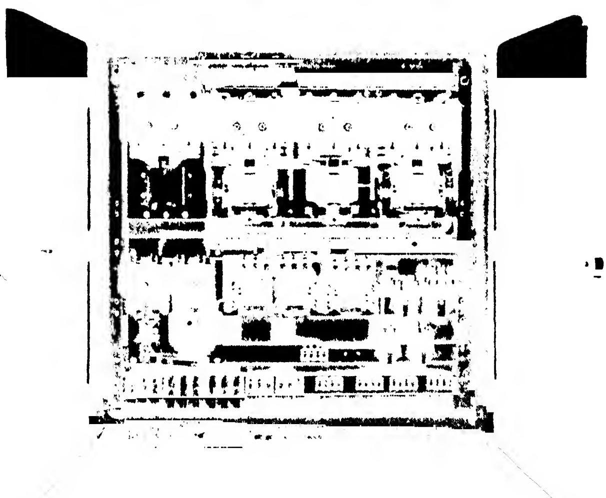


Fig. 40. Push Button-operated Machine-Tool Controller

Slip-Ring Motors. The difference between the squirrel-cage motor and a slip-ring motor rests in the winding of the rotor. Whereas the first has a rotor winding consisting of bars connected at the ends by copper rings, the latter has a winding consisting of short-circuited coils corresponding to the number of poles on the stator winding. Each coil or set of coils is brought to a slip ring on the motor shaft. Since coils are used on the rotor, the slip-ring motor is also referred to as a "Wound-Rotor Motor."

Slip-ring motors are started by inserting resistance in the secondary winding which is the rotor circuit. The value of the starting circuit is governed by the desired starting torque and the losses occurring during starting period. The larger the starting current the shorter the starting time required for a given load.

By changing the resistance in the rotor circuit, any desired torque which the motor can develop between standstill and full speed can be obtained. Every slip-ring motor has a maximum

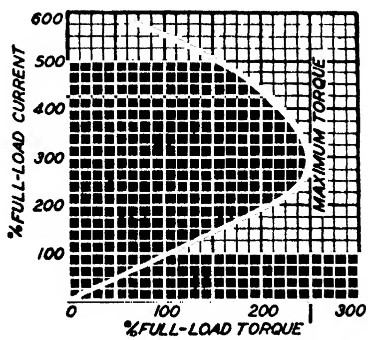


Fig 41 Torque Curve of a Three-Phase Wound-Rotor Induction Motor

torque, which occurs at a certain current value. Increasing the current beyond this maximum torque value reduces the starting torque and is of no value.

Fig. 41 shows the performance curve of a slip-ring motor, and it should be noted that maximum torque occurs between 200 to 300 per cent current.

To determine the secondary current, the following formula can be used:

$$\text{Secondary amp.} = \frac{\text{hp.} \times 746}{\sqrt{3} \times \text{open volts between rings}}$$

A slip-ring motor cannot be thrown across the line, and for starting it is necessary to insert resistance into the rotor circuit in order to get sufficient starting torque. This is brought out in Fig. 41. For smaller motors one to two steps of resistance are sufficient. For larger motors additional steps may be required to eliminate too large current inrushes.

The main applications for slip-ring motors are found where

speed control is wanted or where high starting torques must be obtained with a minimum of current from the line. In connection with punch and drawing presses they provide the high slip necessary for the flywheel to release its stored energy and to obtain quick acceleration of the press following the power stroke. In such application a step of resistance is permanently inserted in the secondary motor circuit.

Manual slip-ring control consists of a primary switch and a

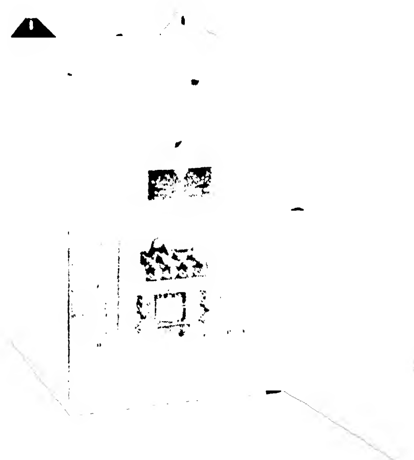


Fig. 42. Face Plate Type Starter with Magnetic Primary Switch

secondary short-circuiting switch. The resistance can be controlled either by a face plate control, a drum controller, or a carbon compression resistor.

Fig. 42 shows a face plate type starter with magnetic primary switch. Moving the operating handle brings in the primary switch, which has two overload relays for motor protection. Further motion cuts out the resistance and in the end position the rotor is short-circuited and motor runs full speed.

Fig. 43 illustrates a slip-ring drum controller. A magnetic primary switch, which is energized by pilot contacts in the drum, can be used, or the primary control switch may be built right in with the drum controller, Fig. 44. In the latter case some outside switch must be provided if no voltage and overload protection is required. Arc shields are provided between the primary switch contacts.

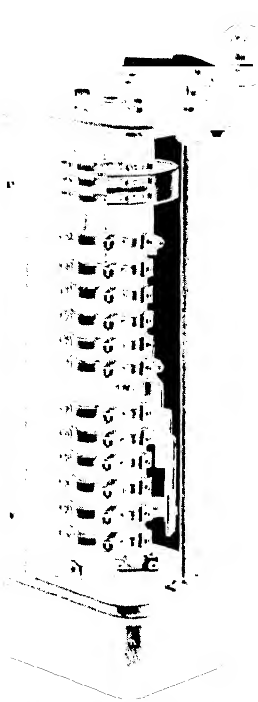


Fig. 43. Drum Controller for Wound-Rotor Induction Motor

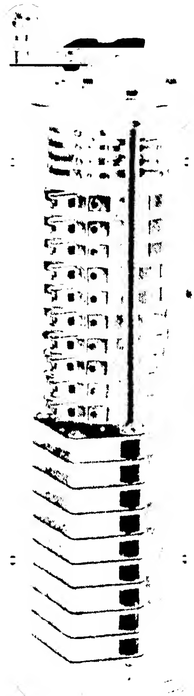


Fig 44. Wound-Rotor Induction Motor Controller with Primary Switch Control

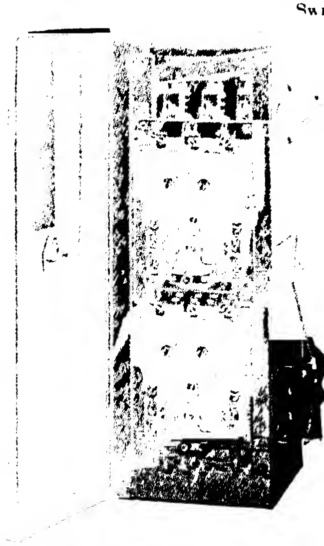


Fig. 45. Compression Resistor Slip-Ring Motor Starter

Fig. 45 shows a compression resistor slip-ring motor starter. Lifting the operating handle to the horizontal position connects the primary; further motion compresses the resistance, accelerating the motor. The last motion energizes the secondary short-circuiting

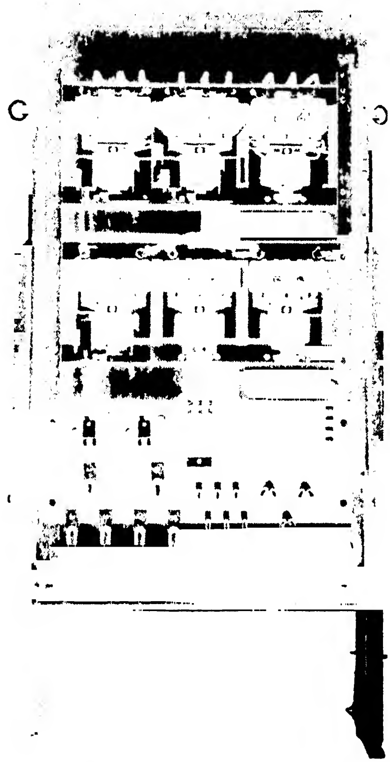


Fig 46 Multistep Automatic Slip-Ring Motor Starter

switch. This type of starter is of the semiautomatic type, since the actual closing of the switches is accomplished by magnetic contactors.

Automatic Starters for Slip-Ring Motors. Full automatic slip-ring motor starters are provided where the actual starting-stopping is accomplished by push button or pilot devices, such as float switches, pressure switches, or thermostats.

Fig. 46 shows a multistep automatic slip-ring motor starter, consisting of a primary contactor and several resistance short-

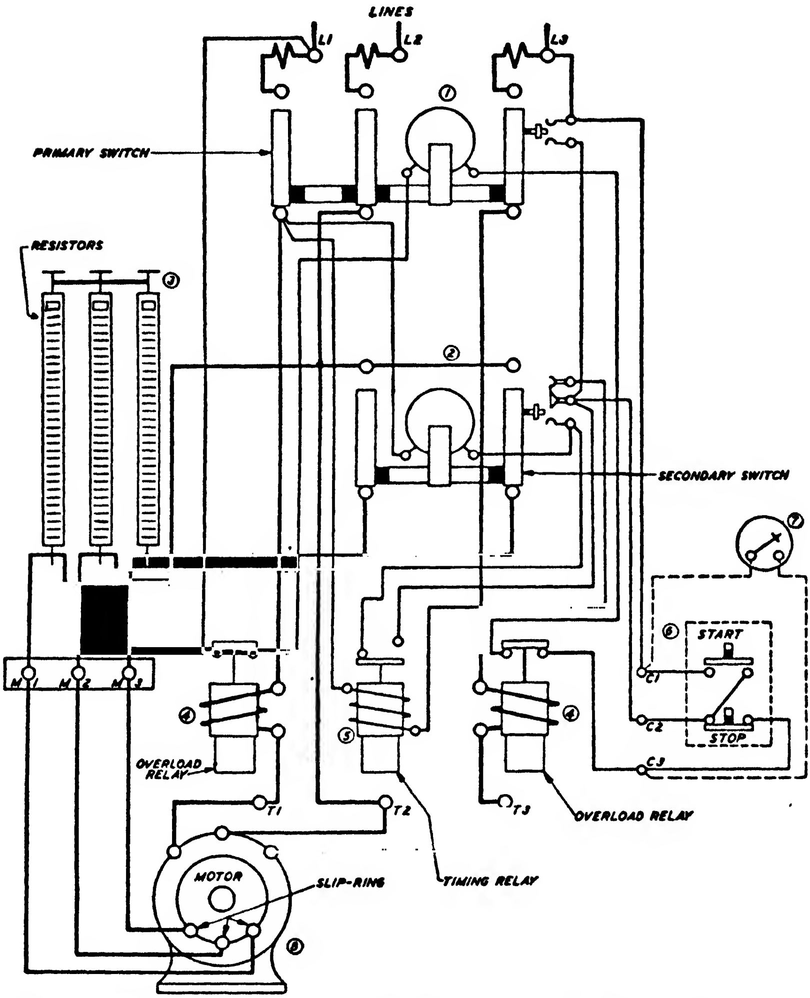


Fig. 47. Single Step of Resistance Automatic Starter with Three-Phase Wound-Rotor Induction Motor

A wound-rotor induction motor is started by inserting resistance in the rotor circuit and connecting the primary directly to the line wires of the circuit. Pressing the start button causes a flow of current from *L1* through the left-hand overload relay contacts, the primary switch contactor coil *1*, through the right-hand overload relay contact, through *C3*, the stop and the start button, *C1*, to line *L3*. When the primary switch closes, connection is established through the stop button *C2* and the two contacts on the primary switch to terminal *L3*, thus holding the primary switch contactor closed when the start button is released. This starts the wound-rotor induction motor with all the resistance in the rotor circuit. One end of each resistor is joined, forming a Star or Y-connection at *3* from the slip-ring or rotor leads *M1*, *M2*, and *M3*.

When a two-wire control is desired, such as a float switch thermostatic control, etc., connect switch *7* as indicated by dotted line.

When the primary switch contactors close they establish a circuit through a timing relay,

circuiting contactors. Acceleration is by time-limit relays. The resistance is shorted in steps at definite time intervals as motor comes up to speed.

For smaller slip-ring motors one step of resistance is often sufficient, chiefly where this motor is used primarily to get sufficient starting torque. The resistance is then adjusted for maximum torque value. Fig. 47 presents the diagram of connection for a single-step slip-ring motor starter, using an adjustable compression resistor.

Synchronous Motors. The synchronous motor is an alternating current generator in which the functions are reversed. This type

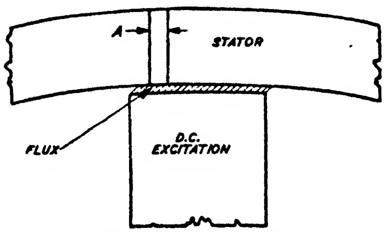


Fig. 48. Diagram Illustrating the Pull-Out Point of a Synchronous Motor

of motor, in its principle, is not self-starting, and special means must be provided to bring the motor up to nearly synchronous speed before it can be connected to the line. This is accomplished by external means, by the use of a starting motor, or, electrically, by the use of a "damper" winding, or by providing the rotor with an additional squirrel-cage winding. The stator receives an alternating-current winding and the rotor a direct-current winding. The speed of the motor is directly proportional to the frequency of the power system and remains constant as long as the frequency of the power system does not change.

By changing the direct current excitation by means of a regulating rheostat, the current taken from the line can be changed. An over-excitation is followed by a "leading" current. This is made use of in connection with power-factor correction. It is one of the

coil 5. When the timing relay operates there is a flow of current from $L1$ through the secondary switch contactor, coil 2, through the timing relay contact, through the contact at the secondary switch and primary switch to line $L3$. When the secondary switch closes the center and lower contacts at the right are joined and the center and upper contacts are opened. This connects the contactor coil of the secondary switch 2 through $L3$ and opens the circuit through a timing relay, allowing it to return to the position shown in the diagram.

main reasons for the use of synchronous motors and is much preferred by power companies, particularly where large motors are involved.

Fig. 48 shows the angle A which determines the power that the motor can exert without falling out of step with the power system.

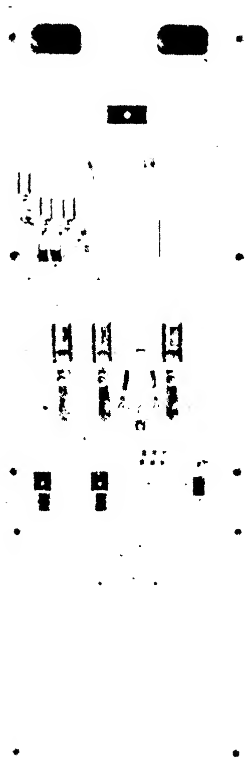


Fig. 49 Low-Voltage Automatic Across-the-Line Synchronous Motor Starter

If the load gets too great the flux will rupture and the machine will fall out of step.

The magnetic flux can be compared to rubber bands pulling the rotor along; an increase in the load increases their stretch. These rubber bands have the tendency to bring the rotor back until the load increases to such a value that the bands "break." The "pull-in torque" can be likened to the pull that these bands can exert

on the rotor and the "pull-out torque," to the pull required to break the rubber bands.

Starting Devices. The starting of a synchronous motor is somewhat complicated, since torque can be developed only after the motor is up to synchronous speed. For that reason, as mentioned above, damper windings or a squirrel-cage winding on the rotor is

Fig 50. High-Tension Synchronous Motor Starter

provided. In the latter case the motor starts like a squirrel-cage motor and when up to speed, the direct current excitation is provided which pulls the motor into synchronous speed.

Fig. 49 shows a low-voltage automatic across-the-line synchronous motor starter, consisting of the line switch, which connects the stator to the line, the field switch, the timing relay, which connects the direct-current field to the motor after a predetermined time, and a field rheostat for adjusting the direct-current excitation. Two

ammeters are provided, one in the line circuit and one in the field circuit to provide means to adjust the direct-current field for best performance.

Fig. 50 shows a high-tension synchronous motor starter. The motor-starting oil switch current transformer and voltage transformers are in back of the panel. All equipment on the front of the panel is low tension, consisting of the ammeters, operating magnet, overload relays, timing relay, and automatic field switch.

Autotransformer type and primary resistance type starters are

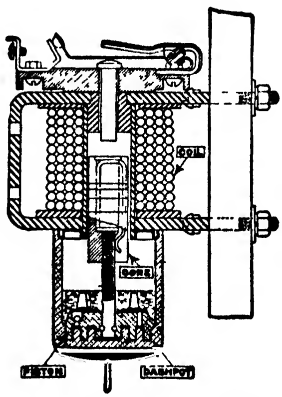


Fig 51. Magnetic Relay with Oil Dashpot

also used. These are similar to those used for squirrel-cage induction motors where current from the line has to be limited or where starting of the driven machine has to be gradual.

Motor Protection. Overload protection for motors is an important function of the starting equipment. Two fundamental types are used. The **magnetic relay** is a coil through which the motor current flows, producing a pull on a core to which a dashpot piston is attached. If the current rises above the value for which the overload relay has been adjusted, the core starts to pull up against the dashing action and, after a certain time, the contacts are opened, de-energizing the starter holding coil, causing the starter to shut down the motor. The time lag is provided so that the relay will not trip on momentary current peaks or during the starting period. Fig. 51 shows a cross section through a magnetic relay with oil dashpot.

The second type of overload protection is the **thermal relay,** which today is the most widely used ~~motor~~ protection. Its function depends on the heating produced on a resistance element by the motor current. After a certain temperature has been attained due to an overload on the motor, a solder melts, allowing a ratchet to turn and opening the relay contacts (solderpot relay); or a bi-metal thermostat is flexed sufficiently to open the relay contacts. Natu-

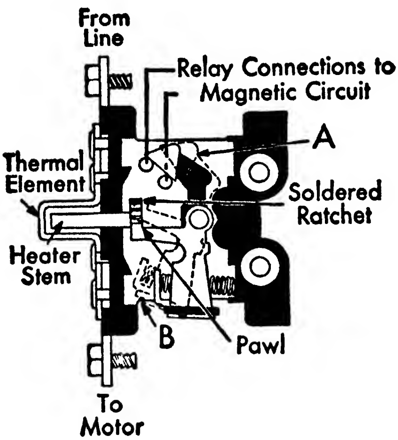


Fig 52 Thermal Overload Relay Closed. Dotted Lines at *A* and *B* Show Open Position

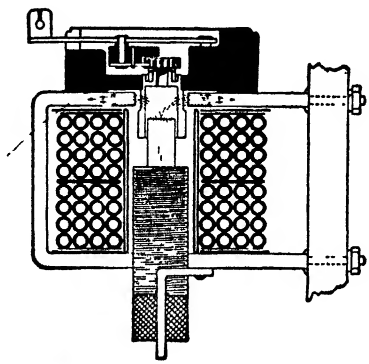


Fig 53 Magnetic Induction Type of Thermal Overload Relay

rally the higher the current, the quicker the heating will take place and the sooner the relay will trip. Fig. 52 shows a thermal relay where the heating is obtained by means of a heater element.

Fig. 53 shows a thermal relay where the heating is obtained by induction. A copper sleeve is used which forms the secondary winding; to this sleeve a ratchet wheel is soldered which will turn to allow the contacts to open when the solder melts. The motor current flows through the relay coils.

Automatic and manual reset overload (O.L.) relays are used. It should be remembered that for two-wire control, such as pressure switches, float switches, hand reset overload relays must be used as, in case of an overload, the equipment will cycle, doing damage to both motor and control.

No-voltage release is another important function of the motor control, mainly in connection with three-wire, and in case the voltage

fails. This feature prevents accidental starting of the motor when voltage returns and protects men and driven machines. Where automatic and semiautomatic control is being used, it is inherent with the magnetic contactors. For manual starters it is provided for by means of no-voltage release magnets, which hold the

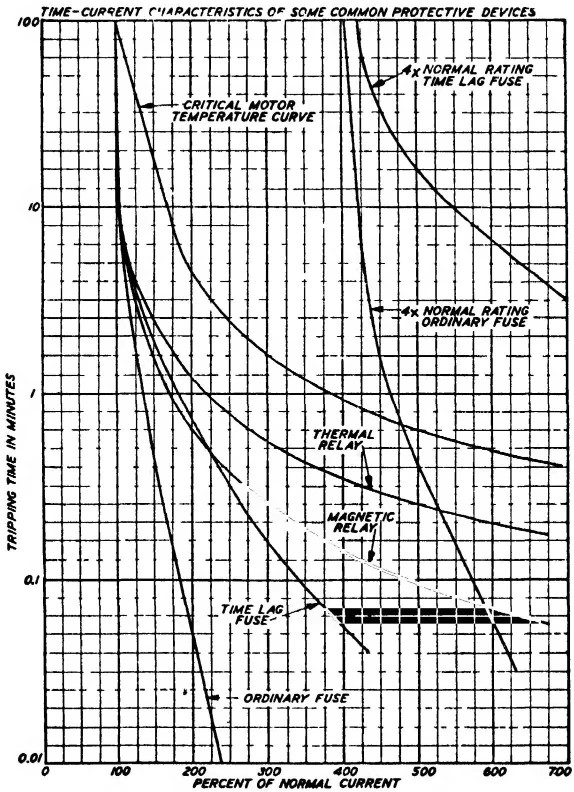


Fig. 54. Curve Showing the Length of Time and Per Cent of Normal Current Required of Different Motor Protective Devices for Operation

control arm up directly or employ a latch which, in turn, is magnetically held.

Fuses cannot be used for motor overload protection, except in connection with small motors which can come up to speed almost instantly. Fuses which, to provide motor protection, may not be larger than 125 per cent full-load current would blow in starting. Fuses in motor control are for short-circuit protection only.

There are manual motor starters which have a double throw switching arrangement, where the fuses are not in the circuit during starting and are only in the circuit after the switch has been thrown into the running position. Starters of this type are seldom used nowadays.

The National Electrical Code specifies the size of fuses to be used in motor circuits. For standard squirrel-cage motors the size of fuse is 300 to 400 per cent of the full-load motor current. When circuit breakers are used in connection with motor circuits, they should be of the instantaneous trip type, set for 9 to 10 times full-load motor current. Time lag breakers will not provide protection to the control equipment.

Fig. 54 shows time-current characteristics of some common protection devices and plainly shows that the ordinary fuse cannot protect a motor.

Contacts and contact material play an important part in motor controls. The sliding contacts, such as are used in connection with drum and face plate type controllers, are limited to their switching ability and require a certain amount of servicing to keep them in good condition. Where copper is used for contact material, the rolling type is used universally. The rolling motion provides that the contact shall roll away from the point where it is first made to a point which has not been burned. Due to the fact that this type of contact has also a slight sliding motion, self-cleaning is effected. Nevertheless copper contacts will in time build up an oxide which produces high contact resistance and must be cleaned off to prevent contact trouble.

In late years silver contacts have been used with great success. These contacts have the unique advantage that they never have to be cleaned, since silver oxide is a conductor. For some classes of motor controls carbon-to-carbon or carbon-to-copper contacts are used. Such contacts are found primarily in connection with elevator controls; the reason is that they positively prevent the welding of contacts and therefore constitute a safety measure. These types of contacts have a rather short life and can be used only in intermittent service on account of the high contact resistance, which would overheat the contacts in continuous service.

ASSEMBLING A MODERN SWITCHBOARD PANEL USED TO CONTROL ELECTRIC POWER IN ARSENALS, AIR BASES, PLANTS AND SHIPS

Courtesy of Westinghouse Electric and Mfg Co East Pittsburgh Pa

CONTROLS FOR ALTERNATING-CURRENT MOTORS

Definitions. The National Electric Manufacturers Association (NEMA) defines a *starter* as "a controller designed for accelerating a motor to normal speed in one direction." More specifically, it is a device for starting and stopping a motor and may provide the additional functions of protecting the motor against overload and no-voltage conditions. A *starter* is shown in Fig. 1.

A *controller* NEMA defines as "a device or group of devices which serve to govern in some predetermined manner electric power de-

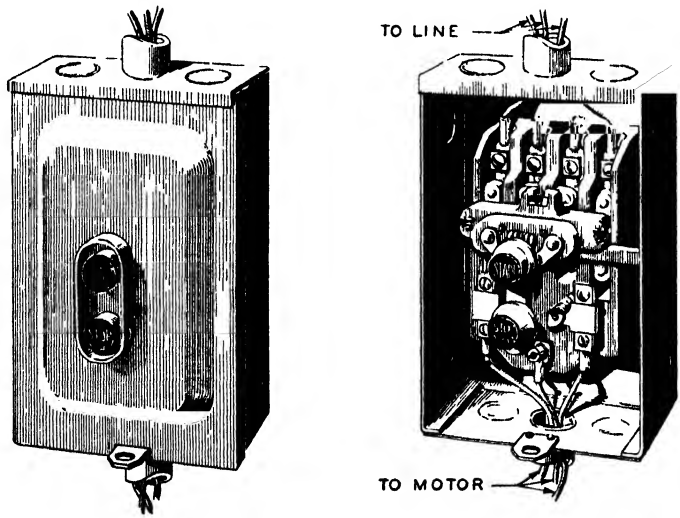


Fig. 1 Exterior and Interior Views of Push-Button Type Alternating-Current Motor Starter

livered to the apparatus to which it is connected." In other words, it performs a number of many possible functions such as starting, stopping, accelerating, decelerating, reversing, speed regulating, and plugging or dynamic braking. It also protects the motor against overload and against voltage failure. Exterior and interior views of a *speed regulator* are shown in Fig. 2.

Classification of Controllers. Controllers, like starters, may be divided into three principal classifications: (1) manual; (2) automatic or power operated; and (3) semiautomatic or combined manual and power operated. Manual controllers are operated by hand and the functions are directly under control of the operator. Automatic controllers are power operated and all of their functions are performed by electrical or electro-mechanical means. On semi-automatic controllers, some functions are performed manually and some automatically.

Manual and semiautomatic controllers are usually employed on applications requiring only a few simple functions such as starting,

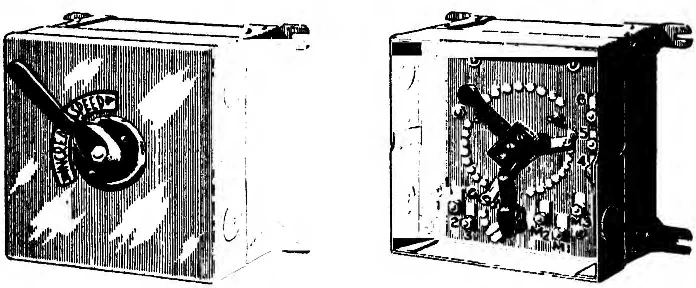


Fig. 2. Exterior and Interior Views of a Manual Speed Regulator for a Slip-Ring Induction Motor

reversing and stopping; or starting, speed changing and stopping. Manual controllers are usually one of the following: Face plate, multiple switch, cam-operated contacts, or drum type. These in turn may be used in combination with magnetic starters or contactors to provide semiautomatic operation.

Automatic controllers are usually considerably more expensive than the other two types, but because they provide more accurate and dependable operation they are usually preferred despite the higher cost. On many industrial applications wherein the functions must occur precisely according to some predetermined sequence or in accordance with changing demands, automatic controllers are indispensable. The operations are accomplished by means of various pilot control devices such as push buttons, limit switches, timing relays, control relays, pressure switches, float switches, or temperature controls.

Types of Motors. With respect to speed characteristics, A.C. motors may be divided into three principal classifications: (1) constant speed; (2) adjustable speed; and (3) multispeed.

Constant-speed Motors. The constant-speed motors are squirrel-cage induction, repulsion induction, split-phase, shaded-pole, and synchronous motors. Three of these types are shown in Fig. 3. The speed of these motors is not adjustable and therefore they are not used for operations which require speed regulation. Despite its constant-speed characteristic, however, the squirrel-cage induction motor, because of its simplicity, ruggedness and low cost maintenance, is more widely used than any other type of motor. When used

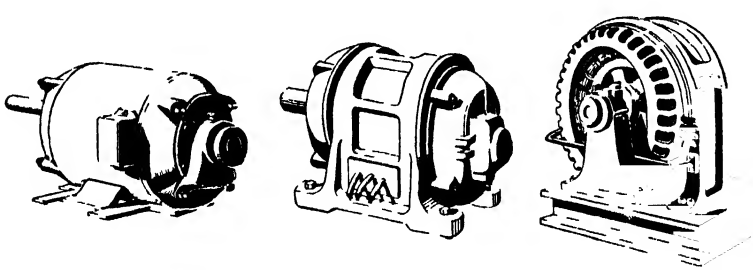


Fig 3 Left Repulsion Induction Motor, Center Squirrel-Cage Motor and Right, Synchronous Motor

singly, its control consists mainly of starting, reversing, and stopping. On many applications a number of these motors of various speed ratings may be used to perform a multiplicity of complex operations, and accurate and dependable automatic controllers are required.

Adjustable-speed Motors. The adjustable-speed motors are slip-ring or wound-rotor induction, repulsion, series, and universal. The last three are usually built in small sizes for driving fans, household appliances and small machines, and the control functions consist mainly of starting and stopping by manual starters. If speed regulation is required, it is obtained by connecting a variable resistance or rheostat in series with the motor.

The *wound-rotor induction motor*, shown in Fig. 4, is used for industrial operations requiring a high starting torque with a low starting current, or requiring speed regulation, or both. Examples of these applications are cranes, hoists, conveyor systems, blowers, pumps, and printing presses. The speed of the motor is adjusted or

regulated by using a controller having resistances in series with each of the three rotor windings. The controller may also be designed to provide additional functions such as reversing, braking, and plugging or quick stopping.

[illegible]. *Multispeed Motors.* Multispeed motors are squirrel-cage induction motors having stators which are wound with one or more windings to provide various speed torque characteristics. The windings may be designed with constant torque characteristics so that the torque is the same for all speeds, variable torque so that the torque decreases

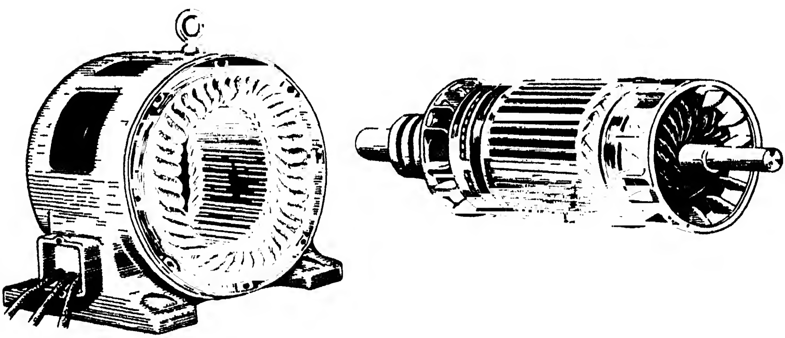


Fig. 4. Stator (Left) and Rotor of Wound-Rotor Induction Motor

with the speed, or constant horsepower so that the horsepower output is constant for all speeds. In the latter case the torque increases as the speed decreases.

On A.C. motors the speed of squirrel-cage induction motors can be changed by changing the frequency of supply or the number of poles on the motor. Because of the high cost of frequency changing equipment, the most practical method of changing the speed is to change the number of poles on the stator. This is accomplished by employing multispeed motors with multiple windings on the stator and using controllers which will make the necessary changes in the connection of the windings.

In recent years multispeed motors have become very popular for use in air conditioning, production processes, machine tool control, and other applications which require only two, three, or four different fixed speeds. The various types of controls for these and for wound-rotor induction motors will be described in the following pages.

MULTISPEED MOTOR CONTROLLERS

Manual Controllers. Manually operated controllers for multispeed motors are principally of the drum-type construction with variations in the mechanics employed in closing the contacts. In general, a *drum controller* (Fig. 5) consists of a cylinder or sector mounted on an insulated central *shaft*, to the end of which is attached an operating handle by means of which the cylinder or sector can be rotated. Attached to the periphery of the cylinder and insulated from each other are copper contacts or *segments* (Fig. 6) against which

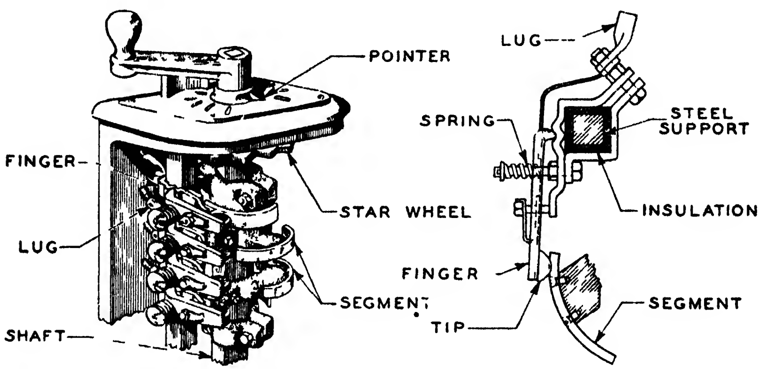


Fig. 5. Interior View of a Drum Controller

Fig. 6. Detail of Segment and Finger of Controller

stationary contacts, in the form of *fingers* mounted on an insulated *steel support* or finger board, are held by *spring* pressure when brought together by rotating the *handle*. To provide the required switching sequence, connections between the rotating contacts and the stationary contacts are made by means of copper straps or wire (not shown).

Positioning for the different speeds for both directions of rotation of the motor is accomplished by means of a roller cam lever attached to the frame of drum controller and a star wheel on the cylinder shaft. The roller of the lever engages notches of the star wheel, Fig. 5, and is held firmly in position by spring tension on the lever.

Drum Switches. Drum controllers (or switches) in a variety of designs for multispeed motors are shown in Fig. 7 and give a general idea of the structure of these devices.

The *controllers*, shown in Fig. 7, more commonly called drum switches, are cam operated and differ somewhat from the general description given in the preceding paragraphs. In this type of con-

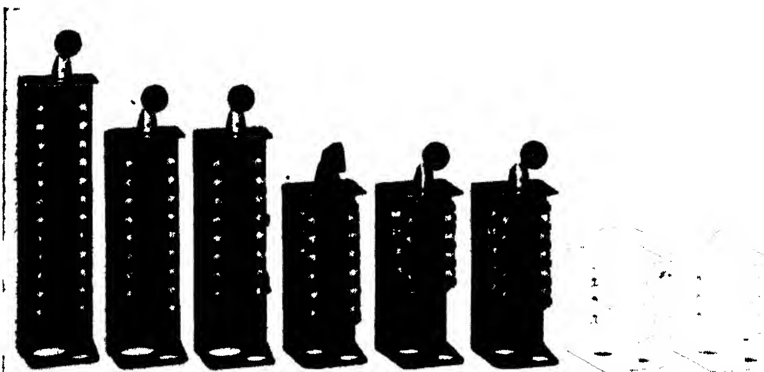


Fig. 7. Group of Controllers for Motors up to Two Horsepower (*A*) Four-Speed Consequent-Pole Nonreversing, (*B*) Three-Speed Consequent-Pole Nonreversing, (*C*) Four-Speed Separate Winding Nonreversing, (*D*) Two-Speed Consequent-Pole Reversing (*E*) D C -Single-Phase and Polyphase Single-Speed Reversing (*F*) Two-Speed Separate Winding Nonreversing (*G* and *H*) Single Speed Single-Phase Reversing

Courtesy of Allen Bradley Company Milwaukee Wisconsin

troller the circuit between the stationary contacts is made by a beryllium-copper *spring contact*, Fig. 8. One end of this contact is fixed permanently on one of the contacts and the other end is free to be moved against the other *stationary contact*. The actuating member

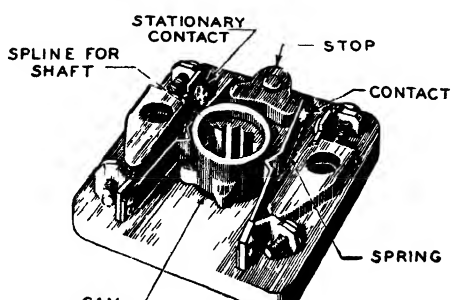
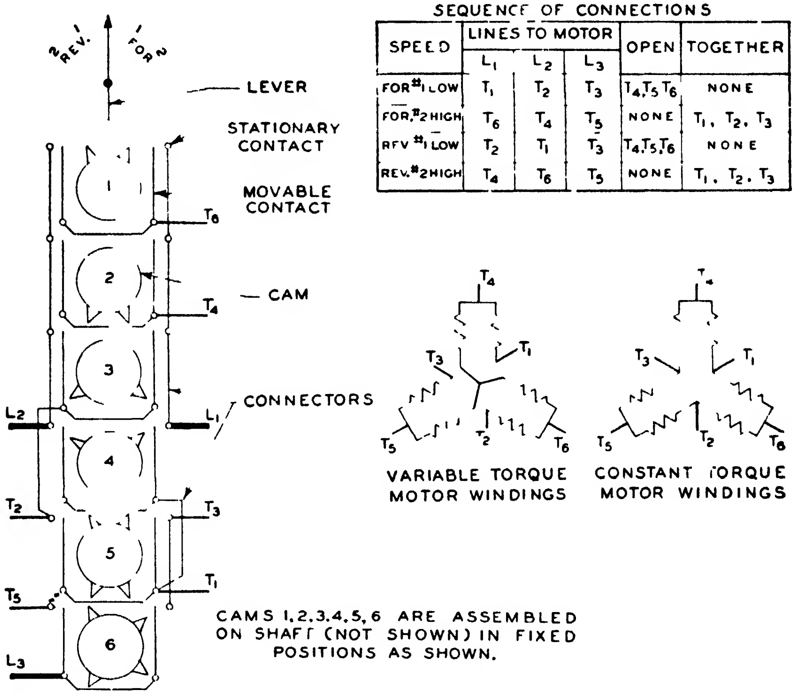


Fig. 8. Detail of Cam and Insulating Support Plate

in this case, instead of being a rotating cylinder, is a series of *cams* of insulating material assembled in fixed positions on the *shaft*. When the shaft is rotated, the cams act on the spring contacts to complete

the circuit between each pair of stationary contacts. A better idea of the construction of the switch can be obtained from the schematic diagram shown in Fig. 9 which is for the *drum switch* (*D*), Fig. 7.

These drum switches are used for controlling small D.C. motors and small single-phase and polyphase A.C. motors. For D.C., single-phase, and single-speed squirrel-cage A.C. motors they are used



SEQUENCE OF CONNECTIONS

SPEED	LINES TO MOTOR L_1	L_2	L_3	OPEN	TOGETHER
FOR.#1 LOW	T_1	T_2	T_3	T_4, T_5, T_6	NONE
FOR.#2 HIGH	T_6	T_4	T_5	NONE	T_1, T_2, T_3
REV.#1 LOW	T_2	T_1	T_3	T_4, T_5, T_6	NONE
REV.#2 HIGH	T_4	T_6	T_5	NONE	T_1, T_2, T_3

Fig. 9 Schematic Diagram of a Two-Speed Variable or Constant-Torque Consequent-Pole Reversing Drum Switch

principally for reversing service. For multispeed motors they are used for two-, three- and four-speed motors.

The schematic diagram of *connections* for a two-speed variable or *constant-torque reversing motor* and *controller* is shown in Fig. 9, and the operation may be explained as follows: When the lever is moved to the forward (*FOR.*) position *1*, or low speed, the cams all rotate 30 degrees clockwise. Cam *4* closes the contacts on its right to make connections between L_1 and T_1; cam *3* closes the contacts on its left to make

connections between L_2 and T_2; and cam *6* closes the contacts on its right to make connections between L_3 and T_3. When the lever is moved to forward *2* position, or high speed, the cams rotate another 30 degrees to make the connections shown in the sequence table. In a similar manner, when the lever is moved to positions *1* or *2* in the reverse (*REV.*) direction, the connections are made as tabulated, with

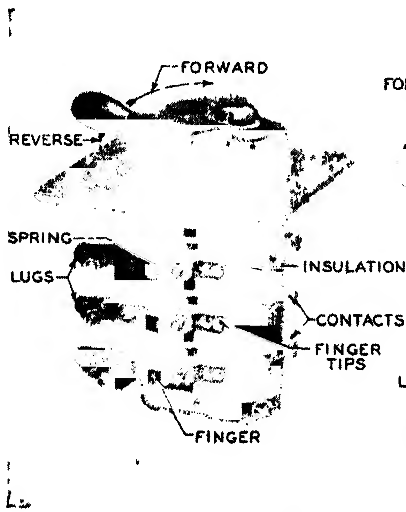


Fig. 10. Hand-Operated Reversing Drum Switch Equipped with Arc Barriers for Use on Five-Horsepower, 220-Volt Single-Speed Squirrel-Cage Motor

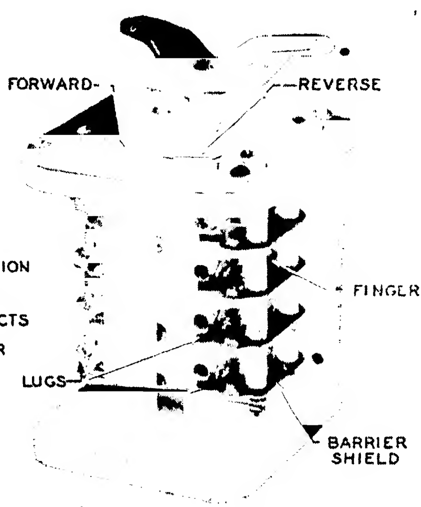


Fig 11. Rope-Operated Reversing Drum Switch Equipped with Arc Barriers for Use on Five Horsepower 220-Volt Single-Speed Squirrel-Cage Motor

Courtesy of Allen-Bradley Company, Milwaukee, Wisconsin

two of the lines to the motor being reversed to reverse the direction of rotation of the motor.

It will be noted that each one of the six cams is of a different structure. Many other constructions are available and, by using the required combinations of cams properly interconnected, an almost unlimited variety of switching sequences may be arranged. Any number of cams and contacts may be assembled into a unit, the number being limited only by the mechanical strength and satisfactory operation of the switch.

These drum switches are also designed for use as meter-reading switches, single and multipole transfer switches, and master control switches. Master control switches can be arranged to obtain almost

any sequence of pilot control that may be desired so as to perform operations which would otherwise require a complicated and cumbersome combination of push buttons and control stations.

Another type of controller which is similar in operation to the one just described is a cam-operated controller in which the contacts are assembled to operate in groups, much like magnetic contactors having one or more poles. The operating mechanism consists of a cam, roller lever, and spring arrangement which produces a snap

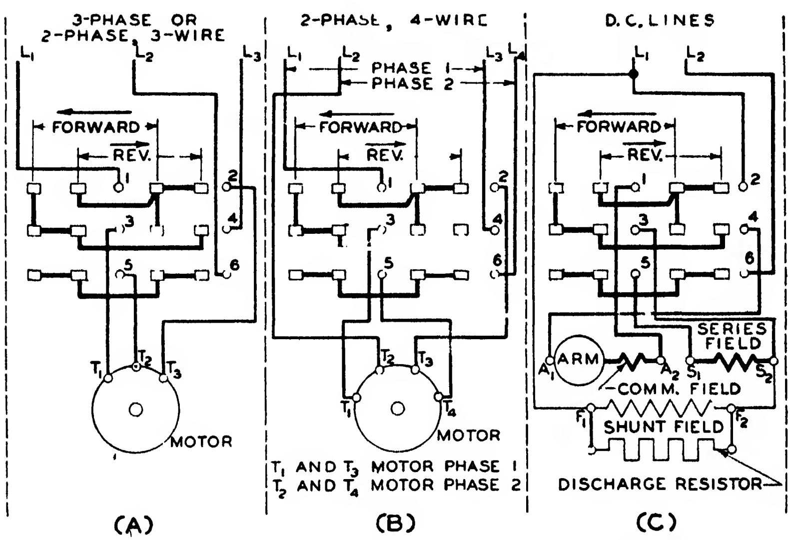


Fig. 12. Connection Diagrams for Reversing Drum Switch for (*A*) Three-Phase, (*B*) Two-Phase, (*C*) Direct-Current Motors

action motion and provides quick action and positive opening and closing of the contacts. Because of this snap action feature, this type of controller is designed to control larger motors up to 30 h.p.

Controllers with Sliding Contacts. Controllers with sliding contacts are shown in Figs. 10 and 11; diagrams for drum switch connections to two types of A.C. motors are shown in Fig. 12 at (*A*) and (*B*); diagram for drum switch connections to a D.C. motor is shown in Fig. 12 at (*C*). These switches are designed primarily to reverse the rotation of D.C. and single-speed A.C. motors, and the switching sequence is obtained in the following manner: In Fig. 12 at (*A*), when the lever is moved clockwise to forward position, the segments on the

cylinder (indicated by small rectangles) move left to bridge contact fingers *1* and *3* (shown by circles) to complete the circuit from line terminal L_1 to motor terminal T_1; fingers *5* and *6* close circuit L_2 to T_2; and fingers *2* and *4* close circuit L_3 to T_3. When the lever is moved counterclockwise to the reverse position, the segments on the

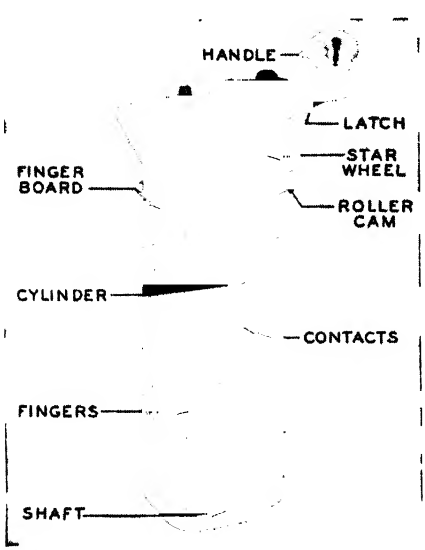


Fig. 13. Drum Controller for Motors under 15 Horsepower

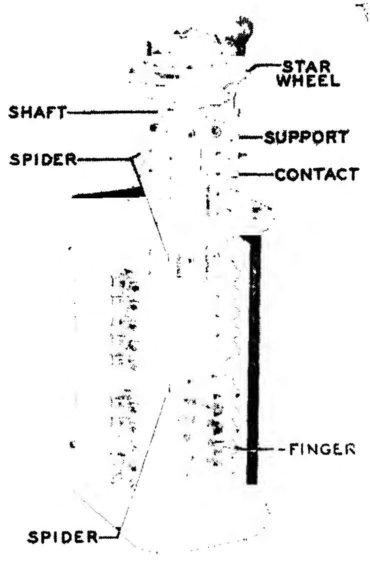


Fig 14. Controller for Motors under 150 Horsepower

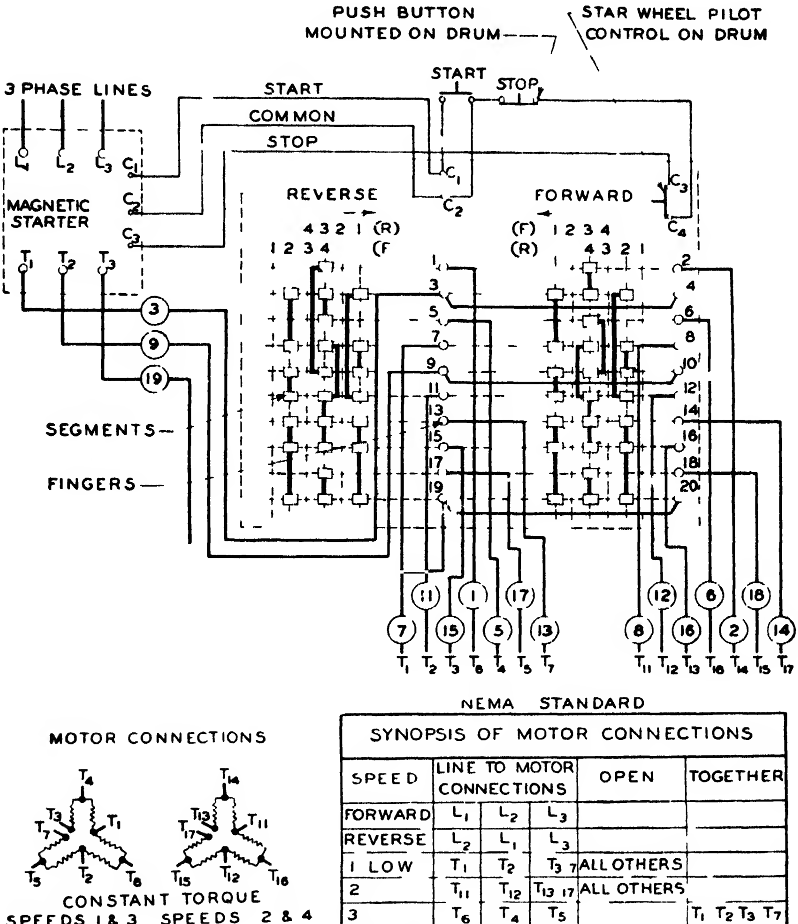
Courtesy of Allen-Bradley Company, Milwaukee, Wisconsin

cylinder move right and bridge fingers *1* and *2*, *3* and *4*, and *5* and *6* to reverse the direction of rotation of the motor.

The circuits may be traced in diagrams (*B*) and (*C*) of Fig. 12, by the same method. In a 2-phase, 4-wire reversing drum switch, one line wire of the phase that is not reversed is connected directly to the motor. This is illustrated in (*B*) of Fig. 12 by the line L_2—T_2.

The *controllers* shown in Figs. 13 and 14 are multispeed controllers of the sliding contact type. Fig. 13 shows a type having a rotating cylinder. It is used for motors up to 15 h.p. Fig. 14, shows a structure in which the rotating member consists of *contacts* attached to insulated *supports* fixed to three *spiders* which are mounted on an insulated *shaft*. (These spiders are clamps having several arms.) This type is

built in sizes to control motors up to 150 h.p. In both of these types the circuits are closed by rotating the cylindrical members so as to bring the movable contacts in contact with the stationary *fingers*, or



SYNOPSIS OF MOTOR CONNECTIONS

SPEED	LINE TO MOTOR CONNECTIONS			OPEN	TOGETHER
FORWARD	L_1	L_2	L_3		
REVERSE	L_2	L_1	L_3		
1 LOW	T_1	T_2	T_3 7	ALL OTHERS	
2	T_{11}	T_{12}	T_{13} 17	ALL OTHERS	
3	T_6	T_4	T_5		T_1 T_2 T_3 T_7
4 HIGH	T_{16}	T_{14}	T_{15}		T_{11} T_{12} T_{13} T_{17}

Fig. 15. Controller Diagram for a Four-Speed Full-Reversing Drum Switch for Use with Consequent-Pole Constant-Torque, Squirrel-Cage Motor

contacts, by a sliding action. Proper contact pressure is maintained by means of springs on the stationary fingers. The developed diagram of the controller in Fig. 15 shows connections to a *magnetic starter* and a table showing the *connections* made to the motor for various posi-

tions of the controller lever. When a magnetic starter is not used, connect supply lines direct to terminals *3*, *9*, *19*, on drum switch and disregard all pilot control connections.

Tracing Circuits. The switching sequence as tabulated can be traced as follows: When the operating lever is placed in the first speed forward position the row of segments (small rectangles) (F)–*1* at the right, make contact with certain fingers (small circles) in the row marked with odd numbers. When cylinder is positioned and contacts are made, the start button is pressed to close the *magnetic starter*. When the button is released the magnetic starter is held closed over its auxiliary contacts C_1–C_2 and over drum-pilot contacts C_3–C_4. The circuit for line L_1 is traced from L_1 to T_1 on starter to finger *3* on controller, through cylinder segments *3–7*, to drum finger *7* and to T_1 on the motor. Next, trace from L_2 to T_2 on starter, to drum finger *9*, through segments *9–11*, to finger *11*, and to motor terminal T_2. Finally, tracing from L_3, the third phase is completed through T_3 on starter, to finger *19* through segments *19–15–13* to finger *13*, to motor terminals T_3 and T_7. This completes the three-phase line to motor connections and at the same time connects together, motor terminals T_3 and T_7 to form a delta connection of the motor windings for slow speed operation.

The openings in the windings of the motor at T_3 and T_7, and T_{13} and T_{17} are there for the purpose of preventing induced currents, by transformer action in the idle winding. That is, when the motor is operating on either winding, the idle winding must be open so that circulating currents which might reach dangerously high values cannot be induced and burn out the winding.

Now bearing in mind that the diagram is drawn to represent an outstretched cylinder, when the lever is moved to the second speed position forward the segments (small rectangles) (F)–*2* at the left make contact with the row of fingers marked by even numbers. In the same manner as explained in position *1*, the three phases can be traced to find that L_1–L_2–L_3 are connected to T_{11}–T_{12}–T_{13} terminals on the other motor winding.

In the third position segments (F)–*3* at the right make contact with the odd-numbered fingers and the lines will be connected to motor terminals T_6–T_4–T_5 on the first winding. Also motor terminals T_1–T_2–T_3–T_7 will be connected together to produce a parallel Y or

star connection of the same winding. In the fourth position the segments in row *(F)–4* at the left make contact with the even-numbered fingers and connections are made as shown in the table for *4* or high speed, making a parallel star connection of the second winding. It will be noted that this controller provides a staggered switching arrangement; that is, first a row of segments on one half of the cylinder makes contact with one row of stationary fingers and in the next position a row of segments on the opposite half of the cylinder makes contact with the other row of fingers. The controller is so designed in order to utilize as much of the surface of the cylinder as possible and thus keep down the size and cost of the controller.

Reversing Motor. For reversing the direction of rotation of the motor, the lever is moved to the reverse position. By tracing the circuits for all four speeds, it will be found that in each case two lines are reversed and connections are made from L_1–L_2–L_3 shown in the *reverse* line of the table, to motor terminals shown in the succeeding lines for speeds *1*, *2*, *3*, and *4*.

Motors up to 10 h.p. can be switched directly by the controller, and in that case the line connections are made to fingers *3*, *9*, and *19* on the controller instead of to the magnetic starter. For motors larger than 10 h.p. it is necessary to use a magnetic switch or contactor to make and break the circuit to the motor so as to avoid severe arcing on the contacts of the controller. Magnetic switches are designed with better arc-rupturing characteristics and, when used with controllers, prevent the burning away of drum contacts, which results from severe arcing.

Interlocking Contacts. The diagram just discussed shows a *star-wheel pilot control* interlocking contact C_3–C_4, which opens the magnetic starter each time the lever is moved from one position to another. In the *off* and all the *on* positions, the contacts C_3–C_4 are closed. A small movement of the lever in any direction opens these contacts and causes the magnetic starter to open before the circuits are broken in the drum switch, thus removing the switching burden from the controller. In consequence of this feature, when the lever reaches a new position the magnetic starter is open and must be reclosed with the start button. This must be done with each change in position of the operating lever.

Another type of interlocking contacts on drum switches called

off position reset permits the magnetic switch to be closed over contacts on the controller which are closed in the *off* position and open in all other positions. Under normal operating conditions the magnetic switch, after being closed with the start button, remains closed for all positions of the lever. However, if the magnetic switch opens because of voltage failure or an overload condition, the switch cannot be reclosed until the controller lever is brought to the *off* position. This arrangement is desirable on applications that require very frequent and rapid operation of the drum switches because the operator needs only to shift the lever for reversing or speed changing and does not have to perform the extra operation of pressing the start button. However, the method cannot be used for motors above 10 h.p. for reasons explained.

Overload protection for multispeed motors may be provided for one or more speeds as desired. In many cases protection is required only for high speed, and in that case the magnetic switch is equipped with one pair of overload relays. For protection on other speeds, the magnetic switch may be equipped with additional relays or a separate overload relay panel may be used to obtain the added protection.

AUTOMATIC MULTISPEED CONTROLLERS

Automatic controllers find a wide field of application with motors used on machine tools, fans, air-conditioning systems, refrigerating compressors, stokers, conveyors, also on bakery, laundry, and textile machinery.

The simpler and most commonly used controllers consist of an assembly of magnetic contactors and magnetic switches, either mechanically, or mechanically and electrically interlocked so as to insure correct sequence of operation. They are equipped with two overload relays for each speed so as to provide dependable protection against sustained overloads at all speeds.

For separate winding motors the number of main switches on the controller is equal to the number of speeds. For consequent-pole motors, wherein one winding is used for two speeds, one contactor is used for one speed and one or more contactors may be required for the second speed for reconnecting the winding and connecting it to the line.

The controllers may be operated by means of push-button sta-

tions, or a combination of push-button stations, limit switches, and other automatic pilot-control devices or exclusively by means of automatic control devices such as float switches, pressure switches, thermostats, control relays, timing relays, time clocks, limit switches, and other devices used in combinations to provide the desired sequence of operation.

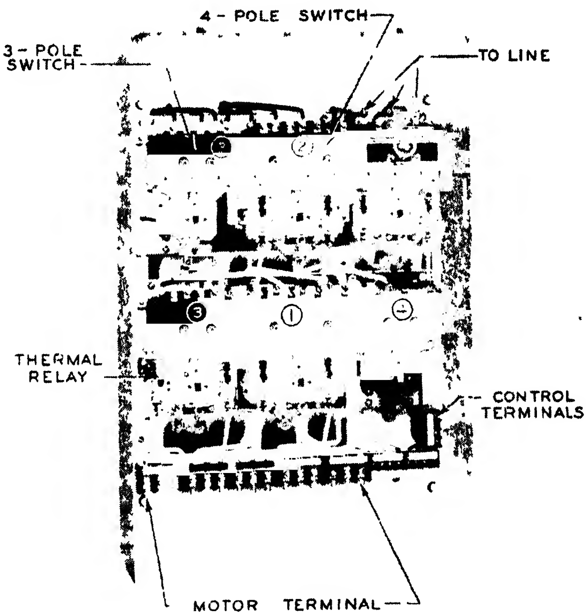


Fig. 16. Automatic Multispeed Controller for a Four-Speed, Two-Winding Consequent-Pole, Constant-Torque Motor

Courtesy of Allen-Bradley Company, Milwaukee, Wisconsin

A typical controller shown in Fig. 16 is designed for controlling a four-speed, two-winding, consequent-pole, constant-torque motor. This type of controller is used on either a fifteen horsepower, 220-volt motor, or on a twenty-five horsepower, 440–600-volt motor. Either a push-button station with indicating *lamps* to indicate the speed at which motor is operating as shown in Fig. 17, or a plain station without lamps may be used to operate the controller. The connection diagram is shown in Fig. 18 and the line diagrams showing the control schemes in simplified form are shown in Fig. 19. The schematic

diagram, Fig. 19, corresponds to push-button connections when made as shown at (*A*) in Fig. 18 and the schematic diagram, Fig. 20 corresponds to push-button connections when made as shown at (*B*) in Fig. 18.

When an indicating push-button station, Fig. 17, is to be used, the wire indicated by the dotted line to terminal C_{10}, Fig. 18, is installed on the control panel. Then a wire is installed from terminal C_{10}, Fig. 18, to the left-hand terminal of the *lamp*, Fig. 17.

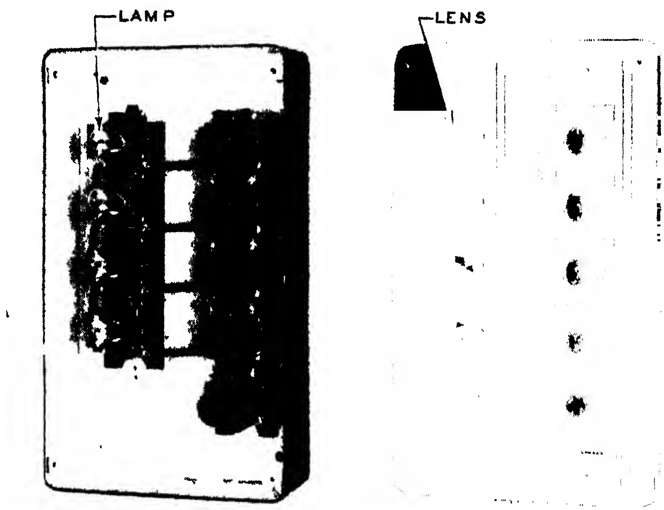
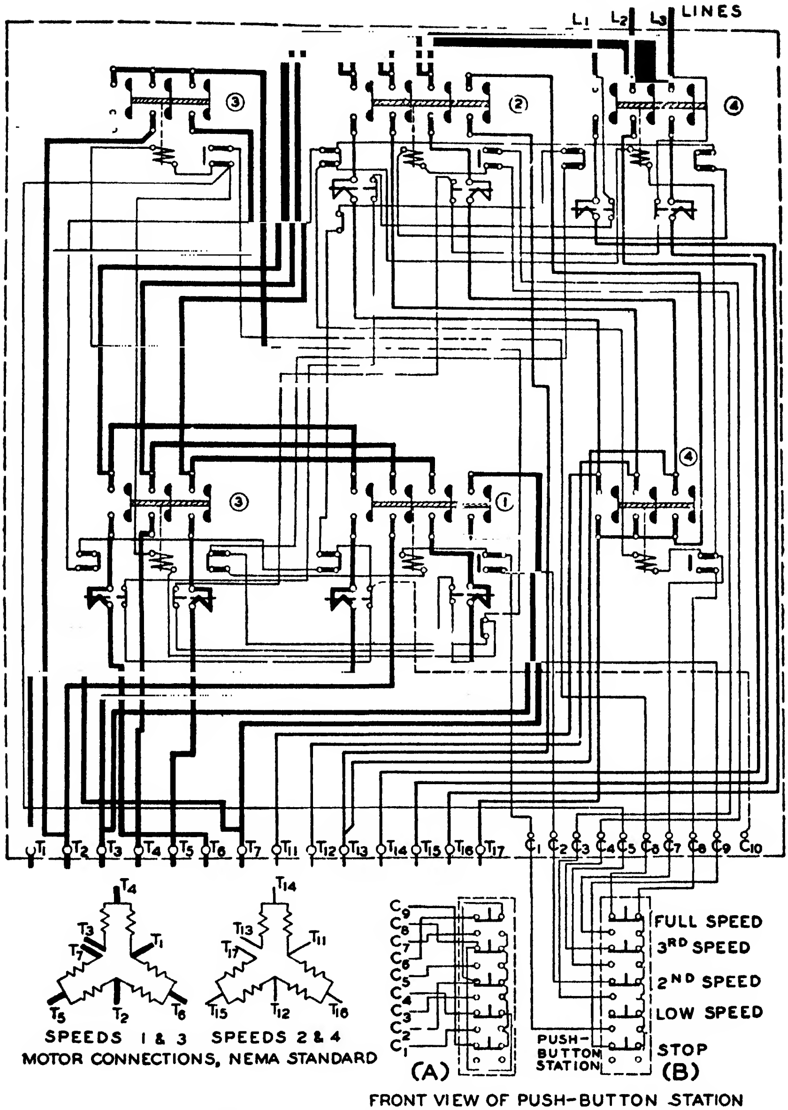


Fig. 17 Motor Control Station with Indicating Lamps
Courtesy of Allen-Bradley Company, Milwaukee, Wisconsin

The magnetic contactors in the main diagram, Fig. 18 and illustration Fig. 16, are numbered to indicate which speeds they control; that is, number *1* closes for the first or low speed, *2* closes for second speed, the two number *3* contactors close for the third speed, and the two number *4* contactors close for the fourth or high speed. Since the two number *3* coils are connected in parallel and the two number *4* coils are similarly connected, each pair is shown as one coil on the line diagrams in Figs. 19 and 20.

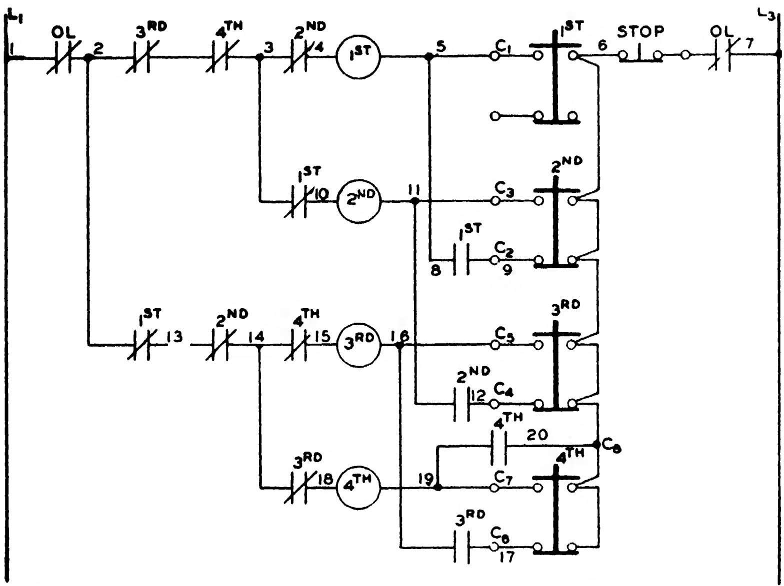
Sequence of Operation. With the control scheme shown at (*B*), Fig. 18 and in Fig. 19, it is possible to start at any speed and increase



SYNOPSIS OE MOTOR CONNECTIONS, 4 SPEED CONSTANT TORQUE MOTOR						
MOTOR SPEEDS		LINES			TOGETHER	OPEN
		L1	L2	L3		
①	LOW	T1	T2	T3-7	NONE	ALL OTHERS
②	SECOND	T11	T12	T13-17	NONE	ALL OTHERS
③	THIRD	T6	T4	T5	T1 T2 T3 T7	ALL OTHERS
④	FULL	T16	T14	T15	T11 T12 T13 T17	ALL OTHERS

Fig. 18. Connection Diagram for an Automatic Four-Speed Starter for Two-Winding Constant-Torque Motor

the speed in sequence as from first to second, to third, to fourth, or from second to third, to fourth and so on. It is not possible to go from one speed to a lower speed without first pressing the *stop button* to disconnect the motor. The sequence of operation will be more readily understood by tracing the circuits in the line diagram. Suppose, first, that the operator presses the *first or low speed button.* This will ener-



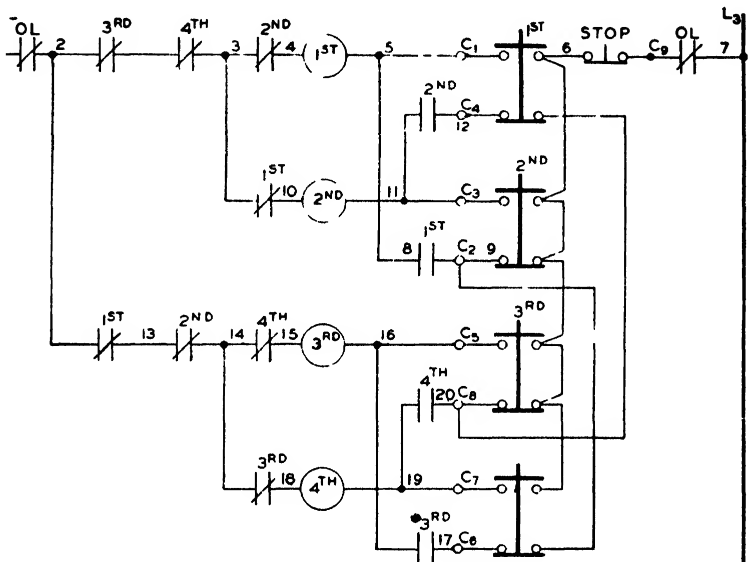
I-SPEED CONSEQUENT POLE — WITHOUT SLOW SPEED COMPELLING RELAY - SPEED INCREASE IN SEQUENCE — REQUIRES STOP TO CHANGE TO LOW

Fig. 19. Schematic Diagram for the Push-Button Station Shown in Fig. 18 at (*B*)

gize the coil of the *1st* speed contactor over circuit *1-2-3-4-5-6-7*, Fig. 19, and contactor will close and lock in through its normally open interlock over circuit *1-2-3-4 5-8-9-6-7*, to make connections from lines L_1, L_2, and L_3 to motor terminals T_1, T_2, and T_3–T_7, respectively, shown in Fig. 18. At the same time that the contactor closes, it opens its two normally closed interlock contacts between *3* and *10*, and between *2* and *13* (marked *1st*, Fig. 19) to avoid any possibility of closing contactor number *2*, *3*, or *4* and to compel speed increase in regular sequence.

If next, the operator attempts to change to the third or fourth speed, it is found to be impossible because the contactors for these

speeds are locked open by the normally closed interlocks previously mentioned as being open. However, it is possible to change to the second speed, for by pressing the *2nd* speed button, number *1* contactor opens, and in doing so closes contactor number *2* over circuit *1-2-3-10-11-6-7*, Fig. 19, which locks in through its normally open interlock over circuit *1-2-3-10-11-12-6-7*, to make connections from the lines L_1, L_2, and L_3 to motor terminals T_{11}, T_{12}, and T_{13}-T_{17}, Fig. 18.



4-SPEED CONSEQUENT POLE — WITHOUT SLOW SPEED COMPELLING RELAY — SPEED CHANGE IN SEQUENCE UP OR DOWN

Fig. 20 Schematic Diagram for the Push-Button Station Shown in Fig. 18 at (*A*)

Now if operator attempts to change to the fourth speed, it is found impossible because the normally closed interlock on contactor number *2* shown between *13* and *14*, Fig. 19, is open to prevent it. However, a change to the *3rd* speed can be made because the operation of the *3rd* speed button opens number *2* contactor to close contactor number *3* over circuit *1-2-13-14-15-16-6-7* which locks in over circuit *1-2-13-14-15-16-17-6-7*, to make motor connections as shown in Fig. 18.

Finally, if operator presses the *4th* speed button, contactors number *3* will open and number *4* will close over circuit *1-2-13-14-18-*

19–6–7, Fig. 19, and lock in over *1–2–13–14–18–19–20–6–7*. From the fourth speed it is not possible to return to a lower speed because the normally closed interlocks on contactors number *4* shown between *2* and *3*, and between *14* and *15*, are open and lock all the other circuits open. Therefore, it is necessary to press the stop button and open contactor number *4* before a lower speed can be selected. After this is done, the operator can select the speed desired. For instance, if he presses the *3rd* speed button, number *3* contactor will close over circuit *1–2–13–14–15–16–6–7* and lock in over *1–2–13–14–15–16–17–6–7*. Again from this speed it is not possible to change to a lower speed because both number *1* and number *2* contactors are locked open by the normally closed contacts between *2* and *3*. Other cycles of operation may be followed through to find that in all cases the motor may be initially started at any speed and the speed increased in sequence, but cannot be decreased without first pressing the stop button.

Speed Change Sequence. The scheme of control shown in Fig. 20 is obtained by changing the connections within the push-button station and making connections to the controller as shown at (*A*) on the main diagram Fig. 18. By tracing the various circuits in a manner similar to that explained for the line diagram, Fig. 19, it will be found that this scheme permits increasing and decreasing the speed in sequence, but that in either direction it is not possible to change to any but the next higher or next lower speed.

Sequence speed control is used in order to reduce the electrical and mechanical disturbance caused by wide and sudden changes in speed. Changing the speed of a motor suddenly by changing the number of poles on the stator produces a momentary polar relationship between the stator and rotor, which in turn causes high currents and disturbing torque conditions that produce a severe braking effect. The motors themselves are usually designed to withstand sudden speed changes when running freely. When connected to the driven load, however, the motors, as well as the load, are subjected to severe mechanical shock which may cause belts to slip or tear, gears to be stripped, or shafts to be sheared.

Selection of Sequence. The nature of the load and the desire of the user of the equipment usually determines the type of speed sequence control to be supplied. Controllers are designed with various other features which provide different methods of accelera-

tion, speed changing, and deceleration. They can be equipped with a control relay so connected as to compel slow-speed starting. The operator must start with *first speed* and then advance successively through *second, third,* and *fourth speeds.* Pushing any other than the low-speed button will produce no result. The controller and motor will operate only after operation of the *low-speed button.*

For automatic sequence acceleration the controllers are equipped with control relays and timing relays to compel slow speed start and to accelerate the motor automatically to the speed selected. When a controller is completely equipped with this feature for all speeds, the operator may press the button for any desired speed and the controller will start the motor at low speed and automatically accelerate the motor in sequence to the speed selected. It will continue to run at this speed until the operator presses the *fourth speed button* or *stop button.*

Controllers are also designed to provide automatic sequence deceleration. With large inertia loads, the severe braking effect resulting from sudden speed changes, as previously explained, may cause damage to the driven machine, the motor, or the operator. To obtain sequence deceleration, the controller is equipped with relays similar to those used for acceleration except that they function to produce an operating cycle exactly opposite. When a lower-speed button is pressed while the motor is operating at high speed, the high-speed contactor opens and the timing relays function to decelerate the motor automatically, with time intervals between each speed change down to the speed selected. For some applications it may be desirable to obtain both the accelerating and decelerating feature, and in that case the controller must be equipped with both types of relays.

For reversing service, the controllers are equipped with additional contactors to reverse the motor at one or more speeds, according to requirements.

WOUND-ROTOR INDUCTION MOTOR CONTROLLERS

Manual Controllers. Multispeed motors have characteristics similar to squirrel-cage induction motors except that they provide a number of fixed speeds. In contrast to this, wound-rotor induction motors (commonly called *slip-ring motors*) are designed to provide adjustable speeds. Since they have two windings—a primary or

stator winding and a secondary or rotor winding—they require controllers that will control both circuits.

The primary control usually consists of a simple device such as a magnetic switch or reversing switch; or it may be an assembly of fingers and segments constituting a primary cylinder mounted on the

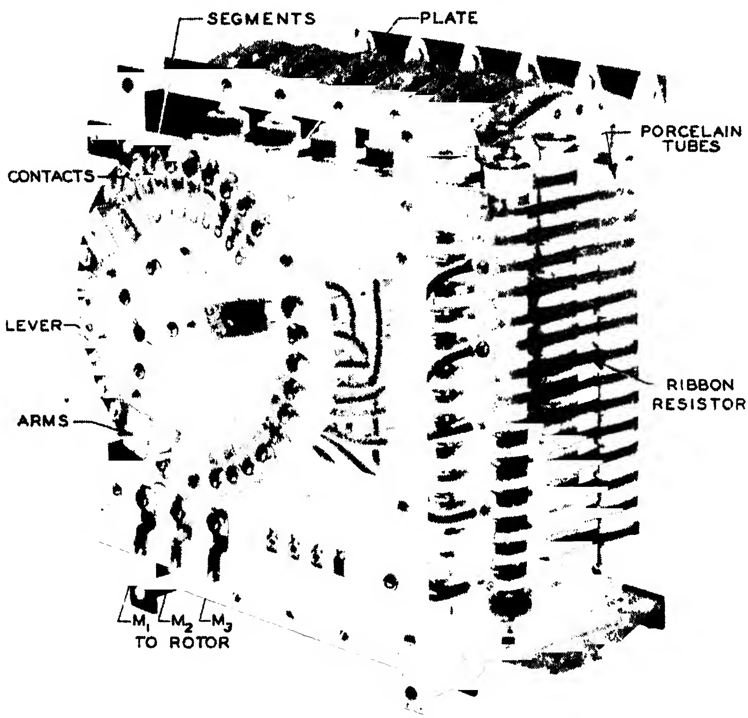


Fig. 21 Interior View Showing the Construction of a Speed Regulator for a Wound-Rotor Induction Motor
Courtesy of Allen-Bradley Company, Milwaukee, Wisconsin

same shaft with the secondary cylinder of a drum controller to make a complete-unit controlling device.

The secondary control is some form of device by means of which the resistance in the rotor circuit can be regulated to obtain the torque or speed required to meet varying load conditions.

Face-Plate Type. Manually operated controllers are built in the face-plate type, carbon-pile type, and drum-type construction. Gen-

erally the face-plate controller (more commonly called *speed regulator*) is constructed in a fashion as shown in Fig. 21 For better illustration of the structure it is shown with enclosure removed. The regulator consists of an operating *lever* with three *arms* carrying contacts under spring pressure which slide over and make contact with the *segments* mounted on a *plate* of insulating material. The *resistors* with numerous taps are connected to the segments on the plate, and as the arms are moved over the segments by the common lever, in one direction or the other, the resistance is progressively *cut in* or *cut out* to change the speed of the motor. The operating handle is similar to that in Fig. 2, and is mounted on the cover of the enclosure so that when the cover is in place the handle engages the face-plate lever which operates the three arms in unison. The arms are mechanically and electrically connected to form a *Y* or *star* as shown in Fig. 22, which also illustrates the controller and motor connections. The resistors also are connected together by connectors *X* and *Y* to make a permanent star connection at the end farthest from the slip rings of the motor. Fig. 23 shows how the resistors are connected and regulated.

Operation of Controller. With the lever arms in the *off* position as shown in Fig. 22, the primary *magnetic starter* is open and the motor is inoperative. When the arms are advanced to position *1*, and while they are advancing, the auxiliary contact lever *E* makes contact first with contact *C* to close the primary starter and then with contact *D* to establish the holding circuit. (The *cutout device*, if one is used, must obviously be closed for operation.) The primary starter locks in over its own auxiliary and over contacts *E–D* on the regulator; these remain closed for all succeeding positions of the main lever *A*. The *motor*, with its primary winding energized and with all the resistance in the rotor circuit, will draw a small current and start rotating at a slow speed. As the lever *A* is progressively advanced clockwise up to position *9*, the resistors are shorted out of the circuit step by step to admit more and more current, and the motor gradually accelerates to full speed. To operate the motor at reduced speed, the lever is placed in a position which will adjust the resistance to a value that will produce the speed desired. Since there are nine points of adjustment, it is possible to operate the motor at nine different speeds. With the final motion of the lever when brought back to the *off* position, contact lever *E* returns to contact *B* to open the primary starter.

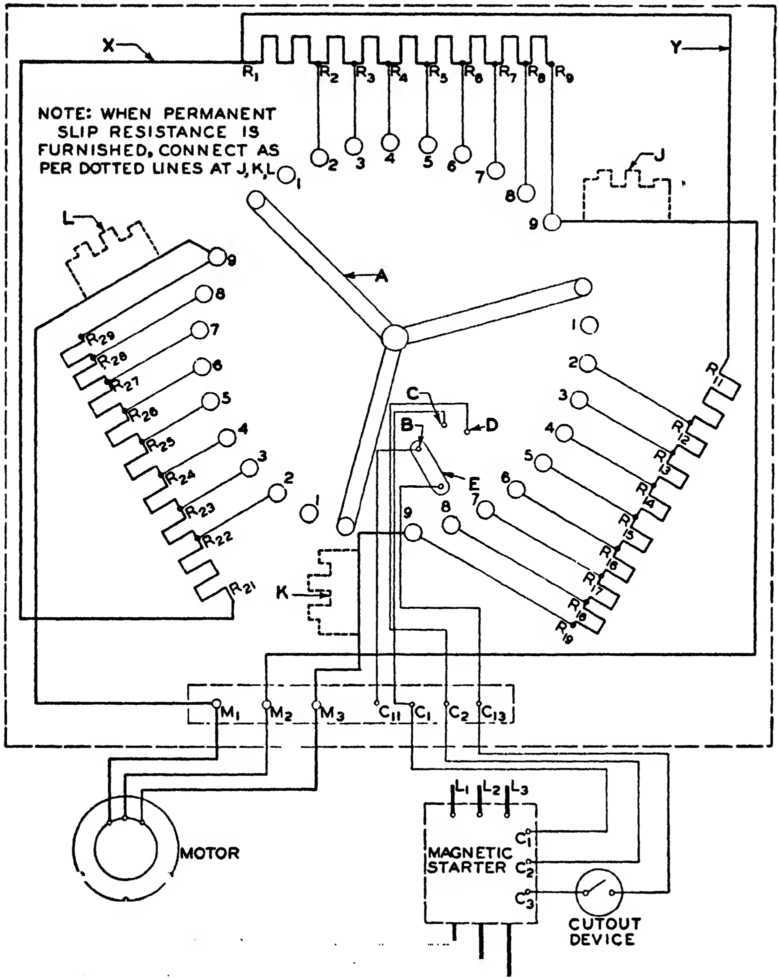


Fig. 22. Wiring Diagram of a Face-Plate Speed Regulator for a Slip-Ring Induction Motor

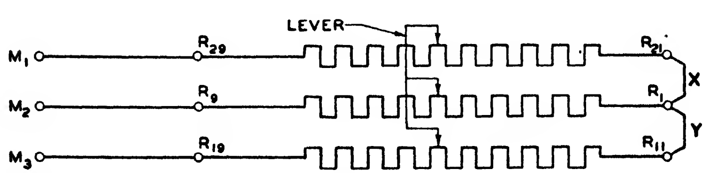


Fig. 23. Schematic Diagram of Face-Plate Speed Regulator

On some operations it might be desired to set the speed regulator for a certain speed and to start and stop the motor without disturbing the lever of the regulator. In that case the primary starter is connected independently of the speed regulator interlocking contacts *B*, *C*, *D*, *E*, and is operated by means of a start-stop push-button station.

The speed regulator just described has a symmetrical arrangement of segments and, therefore, for any position of the lever, the resistances in the three phases are always equal. Regulators are also designed with a staggered arrangement of segments to provide finer speed adjustments. When the lever is advanced to the first point, resistance is shorted out of one phase only. On the next point resistance is shorted in the second phase, on the next in the third phase, next again in the first phase, and so on. With this type of regulator it is possible to obtain up to twenty-one or more points of speed regulation, the number depending upon the design of the face plate. Still finer steps of speed regulation, in fact stepless regulation, can be obtained with *carbon-pile rheostats* or *speed regulators.*

CARBON-PILE SPEED REGULATORS. The *carbon-pile rheostat* and *carbon-pile speed regulator* shown in Figs. 24 and 25, respec-

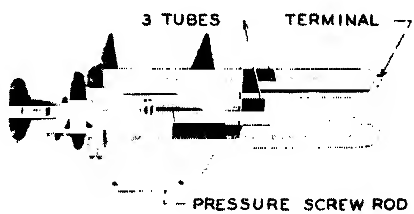


Fig. 24. Carbon-Pile Rheostat
Courtesy of Allen-Bradley Company, Milwaukee, Wisconsin

tively, are similar in construction. The only difference between them is that the speed regulator is equipped with a device by means of which the resistors are entirely short-circuited with the final motion of the *handwheel*. A more detailed explanation of its operation will be given later.

Construction of Carbon-Pile Rheostat. In a broader sense, both of the devices are variable *rheostats* which provide smooth changes in

resistance without steps. Essentially they consist of stacks of processed graphite discs contained within insulated steel *tubes*, the ends of which are fitted with electrodes. In the end of the tube farthest from the handwheel the electrode is insulated from, but rigidly fixed to, the tube and is equipped with a brass stud to provide means for connecting. In the other end the electrode is mounted in an insulating bushing in a manner to permit it to move backward and forward and vary the pressure on the discs. To the outer end of the electrode is

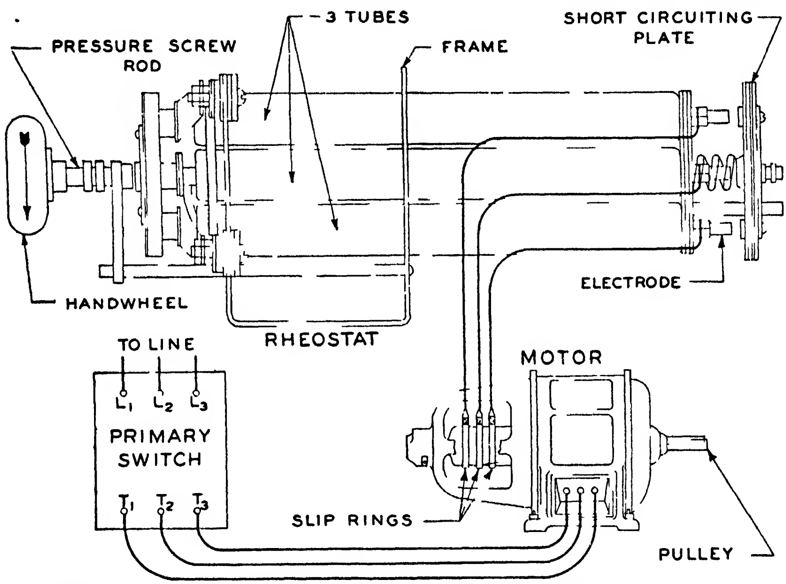


Fig 25 Connections of an Alternating-Current Carbon Pile Speed Regulator in a Circuit

attached an insulating pressure cap and a flexible connector, the free end of which is connected to an insulated terminal on the frame.

The tube resistors are mounted in suitable *frames* equipped with an equalizer, *pressure screw*, and *handwheel*, Fig. 25, by means of which pressure applied to the movable electrode is transmitted to the column of discs. When the handwheel is turned in the clockwise direction, pressure is applied to the columns of discs and reduces the resistance in all the *tubes*. When turned in the counterclockwise direction the pressure is reduced and the resiliency of the discs causes them to spread and thereby increase the resistance in the tubes. The range of resistance between minimum and maximum is approximately 1 to 50.

For example, if discs with a minimum resistance of 1 ohm are used in the rheostat, the maximum resistance obtainable will be 50 ohms. If the minimum resistance is 5 ohms the maximum will be 250 ohms.

The resistance characteristic of carbon discs is determined by the manner in which the discs are processed. It ranges from the specific resistance of graphite, which is very low, to a specific resistance several thousand times that of graphite.

Operation of Carbon-Pile Rheostat. A carbon-pile rheostat such as the one shown in Fig. 24 may be used in conjunction with a face-plate speed regulator by connecting one of each of the tubes or resistors in each rotor circuit, between the ring and its corresponding resistor. The resistance of the rheostat should then be only of sufficient value to provide vernier control between the fixed steps of the face-plate regulator. Under full compression then, the minimum resistance would be low and would permit the motor to operate at near full speed when the face-plate regulator is set for maximum speed. When used in this manner it is not advisable to use a rheostat with a short-circuiting device because of the possibility of shorting the *slip rings* of the *motor* when the face-plate speed regulator is set to operate the motor at reduced speed. Frequently rheostats are used in this way to obtain finer speed regulation, especially on large motors for which a carbon-pile speed regulator alone would be too small.

Carbon-pile rheostats are built with various sizes of tubes and one or more tubes assembled in one frame. The ratings range from a few watts to 10,000 watts or higher. They find a wide field of application in controlling small D.C. and single-phase A.C. motors, electric heaters of all kinds, electroplating currents, battery charging currents, and so on, where stepless resistance and current control is desired.

Carbon-pile resistors as individual units are also assembled and used in many ways in all kinds of resistance starters and controllers.

Operation of Regulator. The *carbon-pile speed regulator* shown in Fig. 25, as previously mentioned, is similar to the *rheostat.* The structure, operation, and characteristics are the same, but it is provided with a *short-circuiting plate* to make it suitable for controlling the secondary circuit of *slip-ring motors,* much as a face-plate regulator or drum controller does. Many operations require stepless speed variation, and to such cases the regulator is ideally suited. It has its limitations as to size and is seldom built for motors larger than 15 h.p.

because of the high cost compared to other types of control. The primary control usually used with this regulator is a primary magnetic switch independently operated.

In order to obtain a slow start and gradual acceleration of the motor, the handwheel of the regulator is turned all the way back counterclockwise before the primary switch is closed. This introduces a high resistance in the rotor circuit, which limits the primary current inrush and the rotor current to a low value. Next, the *primary switch* is closed and the handwheel of the regulator is turned clockwise to reduce the resistance and increase the current to the motor. When the current reaches the value required to produce the necessary starting torque, the motor will start gradually and will continue to accelerate slowly or rapidly, depending upon the rate at which increasing pressure is applied. When the applied pressure reaches the value limited by the turning effort required to turn the handwheel and by the mechanical strength of the regulator, the resistance is so low that the motor runs at nearly full speed. At this point the final motion of the handwheel brings the short-circuiting plate, or ring, in contact with the resistor electrodes to short-circuit the resistance entirely out of the rotor circuit. When the handwheel is turned counterclockwise, the plate breaks contact with the electrodes and introduces resistance into the circuit. By properly adjusting the handwheel it is possible to operate the motor at any speed within the limits of the speed regulation that the regulator will provide, or the limits of speed within which the motor will continue to operate satisfactorily.

DRUM CONTROLLERS FOR WOUND-ROTOR MOTORS

The mechanical structure and operation of controllers for wound-rotor motors is similar to that of multispeed drum controllers, the principal difference being in the construction of the movable member, or cylinder. Typical designs of these controllers are shown in Fig. 26 and Fig. 27. The first is a nonreversing controller which provides secondary control only, and the second is a reversing controller which provides both primary and secondary control.

Nonreversing Drum Controllers. The schematic diagram for the nonreversing controller and its connections to a *primary switch*, resistors, and motor are shown in Fig. 28. The pilot control circuit is

operated by a cylindrical-shaped segment, E, which is mounted on the same insulated shaft with segment A–A. The segment E closes the primary switch over contacts C_1 and C_3 and maintains the holding circuit over C_2 and C_3. The resistance changing device is made of two helical-shaped copper segments A–A which are mechanically and electrically coupled to make one large helical segment that is supported by cast-iron spiders mounted on the insulated shaft. The

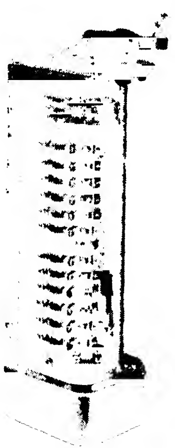


Fig. 26. Drum Controller for Wound-Rotor Induction Motor

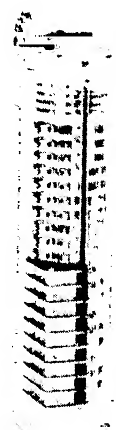


Fig. 27. Drum Controller Primary Switch Control

Courtesy of Allen-Bradley Company, Milwaukee, Wisconsin

segment is so designed that, together with the resistor connections, it maintains a closed Y connection across the three phases or legs of resistors for any position of the cylinder.

When the operating handle which is attached to the shaft is advanced to position *1*, it closes the primary switch to supply power to the stator with all the resistance *in* in the rotor circuit. For all succeeding positions of the handle the primary switch remains closed and, as the power segment A–A rotates into contact with the stationary fingers R_2, R_{12}, R_{22}, R_3, etc., it alternately shorts out sections of resistors in the three phases or legs until, at position *11*, contact is made across R_5, R_{15}, R_{25} to short-circuit all the resistance in the rotor circuit and permit the *motor* to operate at full speed. The speed is

adjusted by placing the operating handle in the position which will provide the speed desired.

Pilot Circuit Interlock. The pilot circuit interlock shown in Fig. 28 provides *no-voltage* protection on all but the first point. For instance, if the primary switch should open because of low voltage or voltage failure when the hand lever is in any position other than position *1*, it cannot be reclosed until the lever is brought back to position *1*. This prevents the motor from starting suddenly and

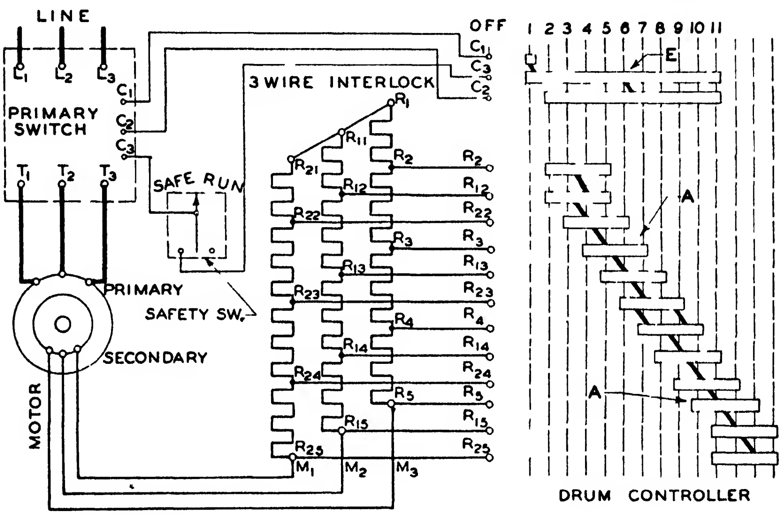


Fig 28 Wiring Diagram for a Nonreversing Drum Controller for Starting or Regulating Duty with 3-Wire Control Pilot Interlock

unexpectedly when voltage is restored. In a measure this feature protects the driven machine and the operator of the machine who might be working on it while it is stopped. However, it does not afford complete protection because it starts the motor on the first point. For example, assume that the motor is *shut down* with the lever in a running position while someone is working on the driven machine. The operator of the controller, thinking he was returning to the *off* position, might pass over position *1* and give the motor a power impulse which might hurt the workman or machine. Rare cases of this are known to have happened, but despite this somewhat objectionable feature, the scheme is used because it is the simplest and most practical way to control both primary and secondary with one lever.

No-Voltage Protection. Where complete *no-voltage* protection is desired, the pilot circuit interlock should be arranged as illustrated in Fig. 29 to provide *off* position reset. The segment E is usually designed so that it can be converted from one type to the other. This off position reset interlock provides *no-voltage* protection on all points, because the motor cannot be started except in the *off* position. A start-stop button must be used to close the primary switch and, when once closed, the switch will not open except in case of overload, no voltage, or pressing of the stop button.

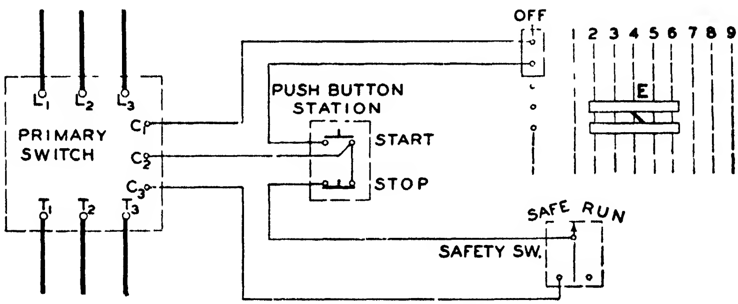
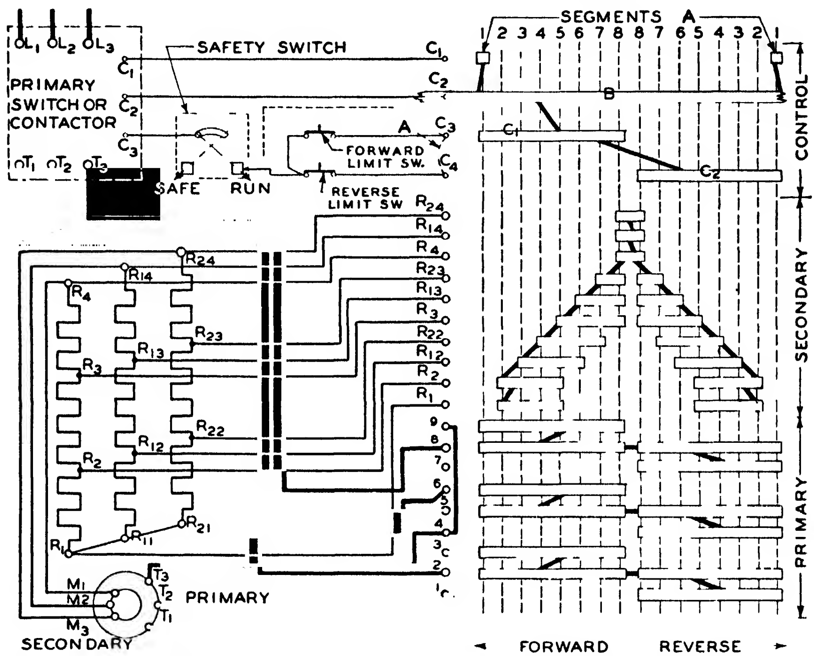


Fig. 29. Pilot Control Connections for Off Position Reset Interlock on a Nonreversing Drum Controller

Reversing Drum Controller. The connections for a reversing type controller as illustrated in Fig. 30 are similar to the connections of a nonreversing controller. In the pilot circuit interlock the *segments A* close the *primary switch* in either direction of rotation of the drum cylinder. Segment B is a complete ring and maintains contact with contact finger C_2 for all positions of the cylinder, including the *off* position. Together with segment C_1 it constitutes the maintaining circuit in the *forward* direction of rotation of the cylinder, and with C_2 it constitutes the maintaining circuit in the *reverse* direction. Fig. 31 shows the *off position reset* interlock connections.

The constituent parts of the movable member or cylinder are the interlock, the secondary control section, and the primary control section, all insulated from one another and all assembled on one common insulated shaft. The *secondary* section is made up of a number of various lengths of cylindrical segments connected together mechanically and electrically ana arranged to accomplish progressive changes in the connections of the resistors for both the *forward* and

reverse direction of rotation. The *primary* section is made of twelve cylindrical segments of equal length assembled in electrically connected groups of four. The three groups are arranged so that the primary lines to the motor are reversed when the operating handle is shifted from one side of the *off* position to the opposite side. By tracing the circuits in the manner explained for the nonreversing



Note When limit switches are not used connect Jumper *A* between C_3 and C_4 and also connect C_3 to safety switch as shown by dotted line

Fig 30 Reversing Drum Controller Having 8 Points Forward and 8 Points Reverse

controller it will be found that the primary magnetic switch closes in position *1*, and remains closed while the resistor sections are successively short-circuited to position *8*. Also, on position *1* the primary power segments close the lines to the motor and hold them closed for all successive points. When the operating lever is brought back to the *off* position, the primary switch and the primary power contacts on the controller open. Next, when the lever is moved in the opposite direction, the cycle is repeated with two of the lines to the motor reversed to produce reverse rotation of the motor.

In most cases a primary magnetic switch is used in connection

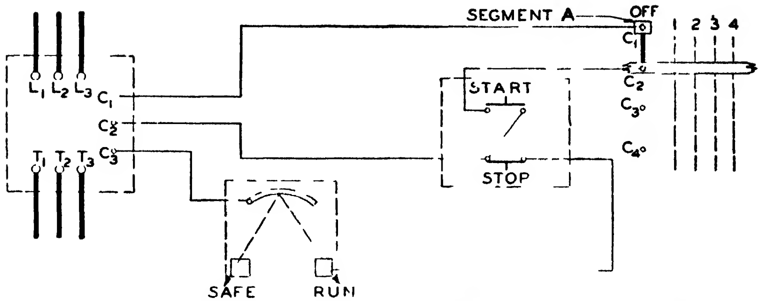


Fig. 31. Pilot Control Connections for Off Position Reset Interlock on a Reversing Drum Controller

with the drum controller in order to obtain overload and no-voltage protection, and to reduce the arcing on the drum contacts. In some cases, however, the magnetic switch is not used and line connections are made directly to the controller as shown in Fig. 32. By referring to Fig. 27 it will be observed that the primary section of the controller is equipped with arc barriers which are mounted on the finger supports

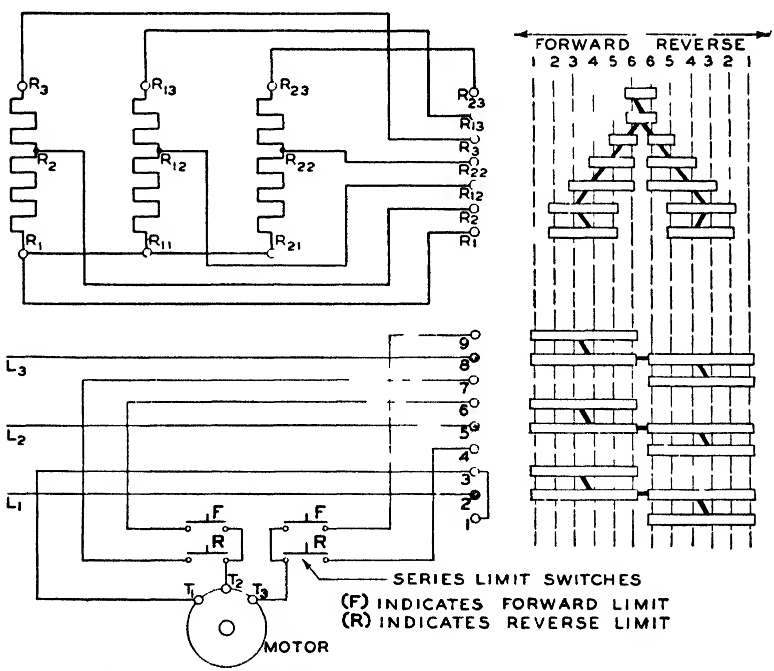


Fig. 32. Reversing Drum Controller Having 6 Points Forward and 6 Points Reverse without a Primary Magnetic Switch

to isolate the power circuits and prevent *flash-over* between lines. This construction permits the controller to be used without a magnetic switch.

Duplex Controller. Another type of *controller,* for which the connections are shown in Fig. 33, is used for controlling the secondary

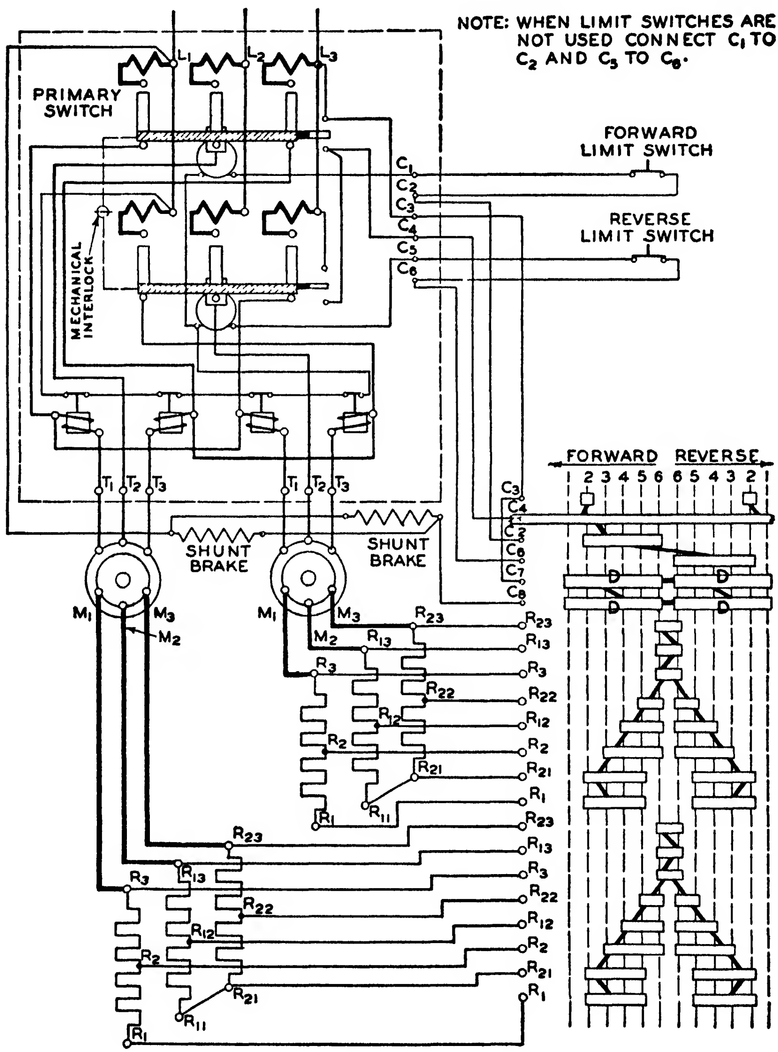


Fig. 33. Two Motor Reversing Controller with Primary Reversing Switch. Drift Point on First Position of Drum

circuits, M_1, M_2, and M_3, of two motors simultaneously. Such controllers are sometimes used for controlling two motors of equal size and characteristics when used for opening and closing large doors, gates or bridges. The reversing operation is accomplished by means of a reversing magnetic switch controlled by *limit switches* and the pilot circuit interlock on the controller. The *reversing switch* is closed on the second instead of the first point, and the first point provides a drift point for the motors equipped with shunt electrical brakes. The motors are slowed down gradually from any running position until, at position *1*, they are disconnected from the line. However, the maintaining segments D remain closed to keep the *brake* energized in the open position and allow the motors to drift or coast for any desired length of time. When the doors, gates, or bridges have reached the desired position, the operator moves the lever to the *off* position to apply the brakes. If the operator should fail to disconnect the motor in time, one of the limit switches, depending on the direction of motion, will disconnect the motor and allow the load to drift into position. Brakes may or may not be used, but on some applications it is advisable to use them to prevent the shock which results when the load has reached its limit of motion.

AUTOMATIC CONTROLLERS. Because of the nature of the applications for which they are used, slip-ring motors are controlled most commonly with manual controllers. The controller is usually attended constantly by the operator, who regulates it to meet constantly changing conditions and requirements. Examples of these applications are cranes, hoist, and material handling machinery of all kinds.

However, automatic controllers find a field of application on operations requiring push-button control from one or more locations remote from the motor and controller, or automatic-pilot control by means of such devices as pressure switches, thermostats, liquid-level controls, limit switches, and timing devices. The four-speed automatic controller shown in Fig. 34 consists of a *main-line switch* with *overload relays*, three *accelerating switches* or contactors, three pilot *control relays*, three *timing relays*, and the speed regulating resistors. In Fig. 35 it is shown controlled by means of a separate five-button station equipped with lamps which indicate the speed of operation. For complete automatic operation, automatic pilot control devices

can be substituted for the *push-button station.* The sequence of the operating cycles will be understood by tracing several of the circuits in the control-circuit line diagram (schematic or elementary diagram) Fig. 36.

Scheme of Operation. When the operator presses the *start,* or *low-speed button,* Fig. 36, the line-switch coil is energized from L_1 through the *OL* contacts, line switch coil, *5,* the start button, *6,* the stop button, *13,* and *OL* contacts to L_3 and closes the *line switch* which maintains the coil circuit over its own interlock *LS.* At this

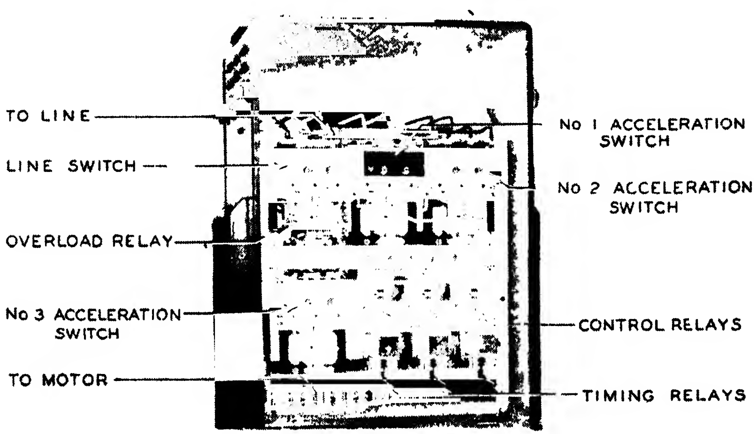


Fig. 34. Fifteen-Horsepower 220-Volt Three-Phase Automatic Wound-Rotor Motor Controller Resistors Are Mounted in Rear of Panel
Courtesy of Allen-Bradley Company, Milwaukee, Wisconsin

stage the motor starts with all the resistance in the rotor circuit and runs at low speed. Timing relay coil TR_1 being connected in parallel with the line switch coil is simultaneously energized and after a predetermined time, depending on the time setting, the relay closes its contacts to set up a circuit in readiness for second-speed operation. The motor will continue to run at low speed until the operator presses the *2nd* speed button to energize *1st accel.* coil and TR_2 coil. The circuit for the 1st accelerator can be traced through the *3rd* and *2nd accel.* normally closed auxiliary contacts, TR_1 contacts previously closed, point *8, 2SP* push button, point *7,* normally closed start button contacts, point *6,* the stop button, point *13, OL* contacts to L_3. The closing of *1st accel.* contactor (see Fig. 35), which maintains

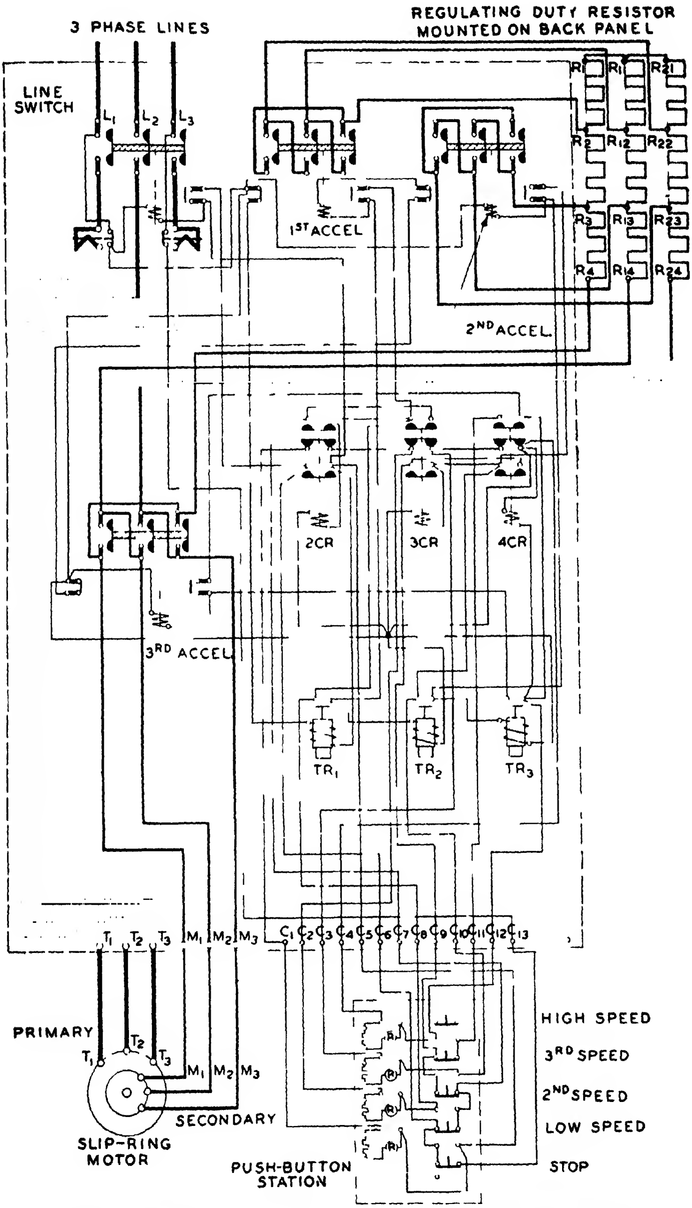


Fig 35 Connection Diagram of a Four-Speed Automatic Preset Speed Regulator

its coil circuit over its own auxiliary contacts, makes connections across the resistors at R_2–R_{12}–R_{22} to increase the speed of the motor. It also opens its normally closed auxiliary contacts to de-energize TR_1 coil. After a predetermined time, relay TR_2 closes its contacts to set up a circuit in readiness for third-speed operation. The motor will now continue to run at the second speed until the operator elects to

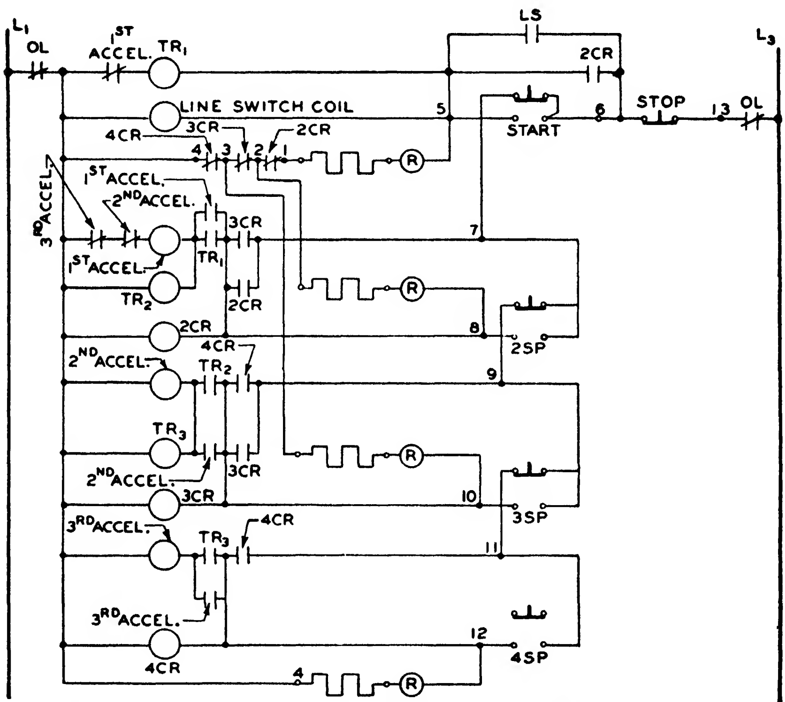


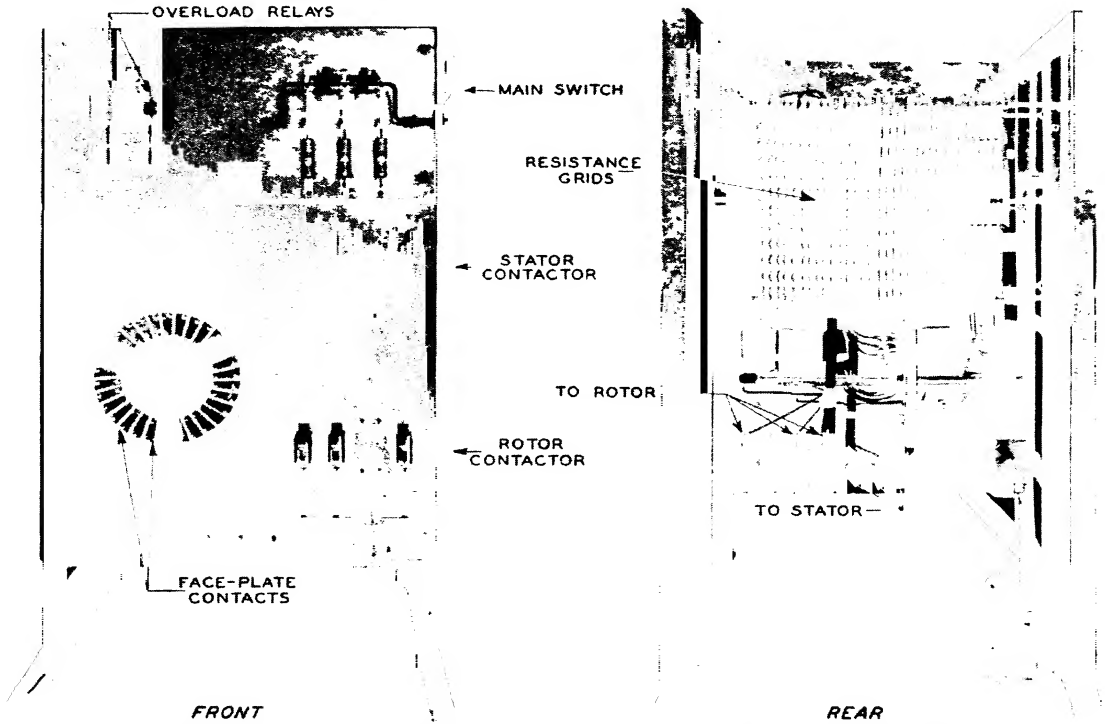
Fig. 36. Schematic Diagram of a Four-Speed Automatic Preset Speed Regulator

press the *3rd* push button (3SP) to close the *2nd accel.* contactor. In the same manner as explained for the first and second speeds, the circuits can be traced for the third and fourth speeds. In tracing circuits it should be borne in mind that, when the device is actuated, normally closed contacts always open, and normally open contacts close.

The controller illustrated provides preset speed regulation which permits the operator to select any speed by pressing only the corresponding push button. For example, if the operator presses the fourth

speed button the controller will, by means of the timing relays, control relays, and auxiliary contacts on line switch and accelerating contactors, automatically start and progressively accelerate the motor from one speed to the next until it is running at fourth or full speed. Suppose now that the operator wishes to operate the motor on third speed and presses the *3rd* button. This will open the *3rd accel.* contactor and close the *1st accel.* contactor over TR_1 contacts which are always closed except when the *1st accel.* is closed or *line switch* is open. From this point on, the controller again automatically and progressively accelerates the motor to the selected third speed.

Automatic controllers, because they are costlier, are not as commonly used as manually operated controllers. However, for many industrial operations which require complete automatic operation or precise sequence cycles with respect to time or mechanical motions, automatic controllers are indispensable. They are designed with various types of cycling and compelling features to provide different methods of operation much similar to those of multispeed controllers.



FRONT AND REAR VIEWS OF AUTOMATIC SPEED REGULATOR PANEL FOR 25-HP, 220-VOLT, 3-PHASE, 60-CYCLE WOUND ROTOR INDUCTION MOTOR

Courtesy of Sundh Electric Company, Newark, New Jersey

USE OF RESISTORS FOR CONTROLLING MOTORS

Definitions. In a discussion of resistors, it is necessary first to make clear the difference between the meaning of *resistor* and *resistance*. The two terms are defined according to the National Electric Manufacturer's Association (NEMA) as follows: "A *resistor* is a device used primarily because it possesses the property of electrical resistance; *resistance* is the opposition offered by a substance or body to the passage through it of electric current, and converts electric energy into heat." In other words, *resistor* refers to the material,

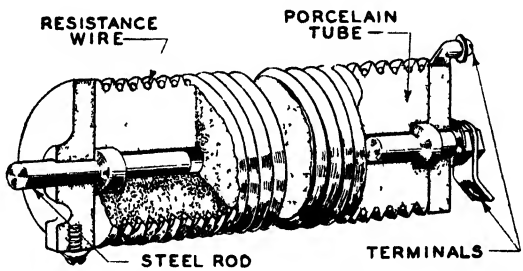


Fig. 1. Wire-Wound Resistor

and *resistance* refers to the current-opposing property of the material. A *rheostat* is defined (NEMA) as, "A resistor which is provided with means for readily varying its resistance."

TYPES OF RESISTORS. Resistors used in electrical circuits for the purpose of operation, protection, and control commonly consist of an assembly of units. They are usually made of resistance wire such as Nichrome or Advance, of fabricated sheet steel, or of iron alloys cast into units called grids. The construction and assembly of units vary with the different manufacturers.

A wire-wound resistor is often made by winding the *resistance wire* in grooves on a *porcelain tube*, Fig. 1. The grooves on the tubes prevent the adjacent turns of wire from coming in contact with each

other and *shorting* part of the resistance out of the circuit. A *steel rod* is used to support and hold the resistor in a frame. The electrical connections are made to the *terminals* at the end of the tube. Sometimes the porcelain tubes may be spaced several inches apart on a metal frame or *end bracket* and the wire wound around the two tubes as a unit in a manner similar to the strip-wound unit in Fig. 2.

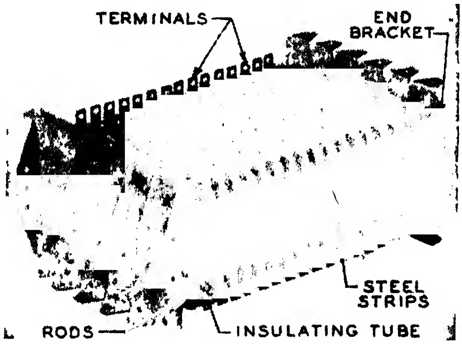


Fig. 2. Six-Unit Assembly of Nonbreakable Resistor
Courtesy of Allen-Bradley Company, Milwaukee, Wisconsin

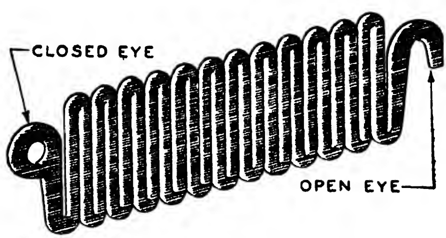


Fig. 3. Cast-Iron or Alloy Resistor Grid

The type illustrated in Fig. 2 is made from *steel strips* of the necessary width for this construction and having resistance characteristics similar to Nichrome wire. The strip steel is cut into correct lengths, sheared in *zig-zag* style similar to Fig. 3, formed and placed on *insulated supporting rods* which are suspended between two *end brackets*. Each turn is provided with means for making a connection to make the resistor flexible with regard to adjusting the resistance between any two points. This type of resistor is known as a *nonbreakable resistor*.

The grid-type resistor is built up out of a number of cast-iron or nickel alloy *grids*, Fig. 3, which are assembled on a supporting frame as in Fig. 4. These grids may have either an *open* or *closed eye*, Fig. 3. The open-eye type grid can be readily replaced in the frame without disturbing the other grids. The details of the assembly are shown in Fig. 5. The *grids* are insulated from the *steel rod* by a *mica tube* and from the *end frame* by *molded insulators*. In assembling, a *mica washer* is placed after every other *grid eye* in order to force the current through the *grid*. A soft *copper washer* is placed between the other

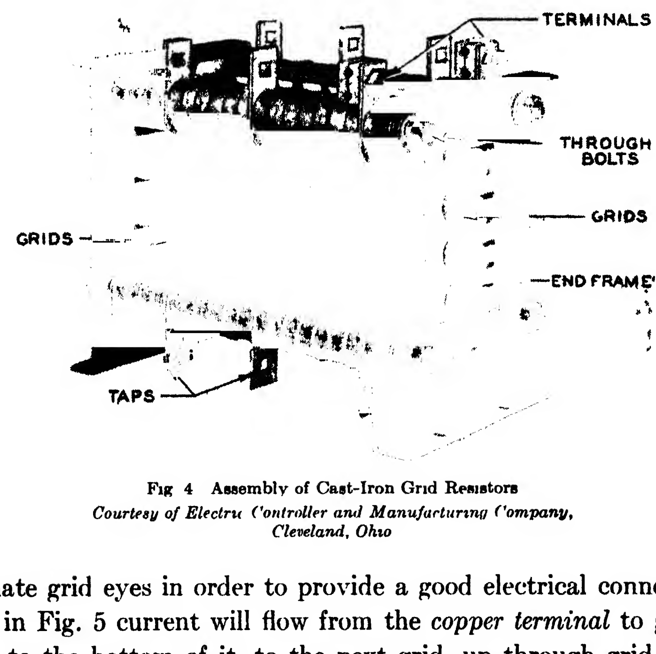


Fig 4 Assembly of Cast-Iron Grid Resistors
Courtesy of Electric Controller and Manufacturing Company, Cleveland, Ohio

alternate grid eyes in order to provide a good electrical connection. Thus in Fig. 5 current will flow from the *copper terminal* to grid *1*, down to the bottom of it, to the next grid, up through grid *2* and grid eye *2*, through the *copper washer* to grid eye *3*, and down through grid *3*, and so on. Between the grid eyes at the bottom of grids *1* and *2* (see Fig. 4) is a copper washer, while grids *2* and *3* have a mica washer between them. In this way the current is forced to travel up and down through the grids in the resistor, Fig. 4, from one terminal to the next. The copper terminals can be readily inserted at any desired place by loosening up the nuts at the end of the *through bolts* of the frame.

Wire-wound resistors are usually used for low currents, nonbreakable resistors for intermediate currents, and cast-grid resistors for high currents. Nonbreakable resistors are not as easily broken as cast grids and furthermore they have better resistance characteristics than cast-grid resistors. The increase in resistance of nonbreakable resistors, due to increase in temperature from 25 degrees C to 400 degrees C, is about 6 per cent, whereas the increase for cast-

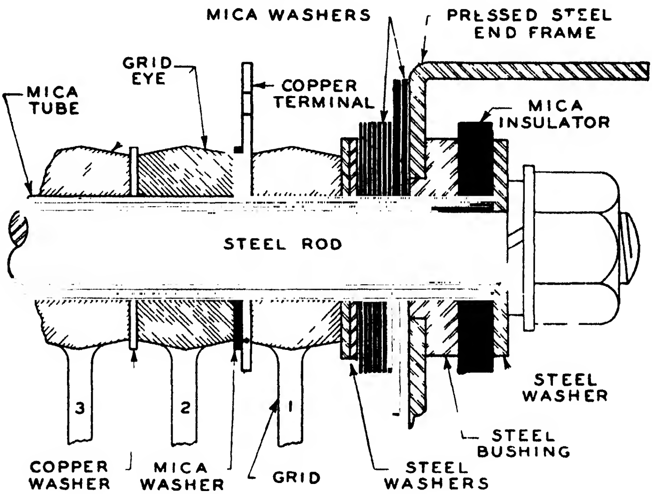


Fig. 5. Detailed Assembly of Resistor Grids on a Steel Frame

grid resistors is from 25 to 40 per cent. For these reasons nonbreakable resistors are used in many cases involving heavy currents, even though they are more costly than cast-grid resistors. For instance, for close speed regulation of a motor at all speeds, a widely changing resistance would be unsuitable; therefore, nonbreakable would be used despite the fact that the motor may draw a high current.

Resistors are used with motor controllers for one or more purposes, some of which are: to limit the current inrush to a motor to protect it from overheating, to prevent power-line disturbances, to reduce excessive strains on belts, chains, gears, shafts and the driven load, and to provide means for varying the speed of motors. They are designed to meet various torque and speed requirements, are rated in ohms, watts, and amperes, and are classified by numbers

applying to duty cycles to be performed as shown in the following table:

CLASSIFICATION OF RESISTORS

Approximate Per Cent of Full Load Current on First Point	Class Numbers Applying to Duty Cycles							
	30 Sec. Out of 15 Min.	5 Sec. Out of 80 Sec.	10 Sec. Out of 80 Sec.	15 Sec. Out of 90 Sec.	15 Sec. Out of 60 Sec.	15 Sec. Out of 45 Sec.	15 Sec. Out of 30 Sec.	Continuous Duty
25	101	111	131	141	151	161	171	91
50	102	112	132	142	152	162	172	92
70	103	113	133	143	153	163	173	93
100	104	114	134	144	154	164	174	94
150	105	115	135	145	155	165	175	95
200 or over	106	116	136	146	156	166	176	96

CLASS NUMBER OF RESISTORS. All of the classes in the table except those in the last column are called *intermittent duty resistors*. Those most commonly used for starting duty are classes *114*, *115*, *116*, *134*, *135*, and *136*; and for intermittent regulating duty, classes *153*, *154*, *155*, *163*, *164*, and *165*. The classes in the last column are for continuous duty, and those most commonly used are classes *92*, *93*, *94*, and *95*. *Intermittent duty* is defined (NEMA) as, "a requirement of operation or service consisting of alternate periods of load and rest so apportioned and regulated that the temperature rise at no time exceeds that specified for the particular class of apparatus under consideration,"—in this case, resistors. *Continuous duty* is defined as, "a requirement of service which demands operation at substantially constant load for an unlimited period."

A class 114 resistor is an intermittent duty resistor designed for starting service, with sufficient capacity to withstand a 5-second start repeated every 80 seconds, and an ohmic resistance to limit the current inrush on the first operating point of the controller to 100 per cent of the full-load motor current. A class 115 resistor would have the same capacity as one of class 114, but its ohmic resistance would be designed to limit the inrush current to 150 per cent of full load.

A class 153 resistor will withstand starting and intermittent speed regulating for periods of 15 seconds out of every 60 seconds and will limit the initial current to 70 per cent of full load. Resistors of the *160* and *170* series have capacities to withstand longer operating cycles and those of the *90* series have capacities to operate continuously.

TORQUE CLASSES OF MOTORS. The torque requirements of all the different kinds of driven machinery can be divided into three general classes; *constant torque, variable torque,* and *constant horsepower.* A *constant torque load* is one which draws approximately the same current from the motor at all speeds. Examples of machines drawing such loads are plunger-type pumps and compressors, constant pressure blowers, conveyors, and all machines in which the load consists principally of friction. A *variable torque load* is one in which the torque requirement decreases as the speed decreases. Machines such as centrifugal pumps, fans, blowers, compressors, and others having considerable inertia or flywheel load are representative of this type. The *constant horsepower load,* which is less common than the other two, is one in which the horsepower is practically constant for all speeds. Since horsepower is proportional to the product of speed and torque it naturally follows that the torque must increase when the speed decreases. Metal and wood processing machines and certain types of machine tools draw constant horsepower loads.

Speed-regulating duty resistors, for use with slip-ring motors, unless otherwise specified are usually designed to limit the inrush current to 100 or 150 per cent of full load, and to provide 50 per cent speed reduction and regulation. Slip-ring motors will perform satisfactorily at speeds ranging from full speed down to 50 per cent speed for all types of loads. For variable torque loads they will perform satisfactorily for speeds as low as 25 per cent.

CALCULATING RESISTANCE. In order to provide 50 per cent speed reduction, the resistor must absorb 50 per cent of the power delivered to the rotor of the motor. Therefore, for constant torque, since the torque remains constant and current is directly proportional to torque, the resistance is determined by the formula:

$$R = \frac{\text{Volts between Rings}}{1.73 \times \text{Full Load Amperes per Ring}} \times 0.50 \qquad (1)$$

However, even for so-called constant torque loads the current at reduced speeds usually is lower than at full speed, and to insure 50 per cent speed reduction the current at this speed is assumed to be 80 per cent of full load. Formula (1) is therefore modified to read:

$$R = \frac{\text{Volts between Rings}}{1.73 \times 0.8 \times \text{Full Load Amperes per Ring}} \times 0.50 \qquad (2)$$

However, the capacity of the resistors must be sufficient to carry full-load current at all speeds so that it will not overheat or burn out in the event that the current does remain constant.

For variable torque applications (commonly called *fan duty*) the current at 50 per cent speed is assumed to be approximately 33 per cent of full load and the formula used for determining the resistance is:

$$R = \frac{\text{Volts between Rings}}{1.73 \times 0.33 \times \text{Full Load Amperes per Ring}} \times 0.50 \qquad (3)$$

The current capacity of the resistors is tapered from full-current capacity at full speed, down to 33 per cent of full-current capacity at 50 per cent speed.

For starting duty and for intermittent regulating duty the resistance is determined by the formula:

$$R = \frac{\text{Volts between Rings} \times 0.90}{1.73 \times \text{Allowable Inrush Current}} \qquad (4)$$

The factor 0.90 is used to make allowance for voltage drop in the lines, motor leads, and the losses in the rotor. The capacity of the resistors is designed to meet the specific requirements of the load.

DYNAMIC BRAKING. On some industrial operations it is desirable or necessary to stop a motor quickly instead of allowing it to coast to a stop. Various devices and methods are used to accomplish the result either mechanically or electrically. Motors may be stopped with hand brakes, mechanical brakes, or magnetic brakes, all of which are mechanical in their operation. They may also be stopped electrically by methods called *dynamic braking* and *plugging.*

Dynamic braking consists essentially of converting the action of a motor from motor action to a generator action. When it is desired to stop an A.C. motor quickly, the stator or primary winding is disconnected from the A.C. power lines and is excited from a D.C. source of supply. When running normally as a motor, the primary or stator field revolves at a speed called *synchronous speed,* which depends on the number of poles and the frequency (cycles). Current is induced in the shorted rotor bars or windings to produce poles which are attracted by the primary poles to produce rotation. When the stator winding is energized with D.C. to establish a stationary

field while the rotor is rotating, the rotor bars generate a high current. The current produces a rotor field which reacts with the stator field to provide a retarding torque that stops the motor.

Various methods are employed on both manual and automatic controllers to accomplish the transfer of power and to regulate it to produce the desired amount of braking action. A simple illustration using the definite time principle and one fixed step of resistance for one step of braking is shown in Fig. 6.

The *motor* is started by closing the *start button* which closes the *A.C. switch* to supply A.C. power. The starting switch which maintains its coil circuit over auxiliary interlock contacts C_1–C_2 is equipped

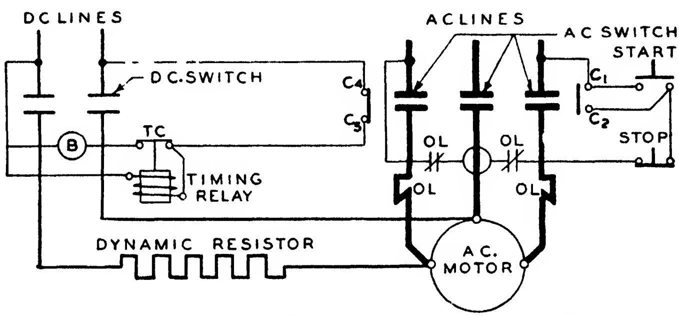


Fig 6 Connection Diagram of One-Step Dynamic Brake

with additional normally closed interlock contacts C_4–C_5. These contacts open when the A.C. switch closes and break the D.C. circuit When the motor is disconnected from the *A.C. lines* by pressing the *stop button* to open the A.C. switch, auxiliary contacts C_4–C_5 close and energize coil B which closes the *D.C. switch* or contactor to supply D.C. power to the motor for a length of time depending on the setting of the *timing relay*. When the timing relay functions it opens its contacts TC to open the *D.C. contactor* or *switch*. The timing relay coil remains energized to hold the circuit for coil B open until it is opened again by the closing of starting switch. At this time the timing relay coil is also de-energized to be in readiness for the next braking operation. The time in which the motor will stop is determined by the amount of D.C. current supplied to the motor, and the current is adjusted by introducing the correct amount of resistance either by means of a tapped fixed resistor or a variable rheostat. The timing

relay is adjusted to function when the motor has stopped or attained the desired reduced speed. Whereas dynamic braking may be employed with A.C. motors, it is more suitable for use on D.C. motors. A more practical method of stopping A.C. motors electrically is by means of plugging, which involves only A.C. power and A.C. equipment.

ELECTRICAL BRAKING BY PLUGGING. Most A.C. motors, both single and polyphase, can be built for reversing service. Polyphase A.C. motors are inherently reversible because they can be reversed by merely reversing any two lines. When the lines are reversed while the motor is running, a counter-torque is developed which causes the motor to stop quickly and then start running in the opposite direction. If the power is interrupted at the instant that the motor starts in the opposite direction, the rotor will turn slightly and then stop. This method of stopping is called *plugging* and the device used, in conjunction with a reversing controller to accomplish quick stopping is called a *plugging switch* or a *zero speed switch*. A *plugging switch* is designed to stop the motor, but not at zero speed. A *zero speed switch* is a plugging switch incorporating a sensitive governor which functions to stop the motor at exactly zero speed.

Plugging switches are designed in various ways so that they can be belt driven from an auxiliary pulley on the shaft of the motor or driven machine, geared to the shaft, or directly coupled to the shaft. A plugging switch designed for direct coupling is shown in Fig. 7. The schematic diagram in Fig. 8 illustrates a plugging circuit consisting of an across-the-line reversing switch (*starting switch* and *plugging contactors*), and a *plugging switch*. A plugging switch, Fig. 7, consists of *solenoid, friction wheel*, pivoted *friction arm* equipped with *brake lining*, and a switching mechanism.

When the motor is started, the solenoid is energized and raises the friction arm (which is under spring tension) free from the friction wheel to permit contact disk D to float in the neutral position. When it is desired to plug the motor, the operator presses the *stop button* to disconnect both the *starting switch* and the *solenoid* in the *plugging switch*. The friction arm is pulled down by the spring against the rotating friction wheel, which moves the arm around so that contact disc D closes the circuit between contacts *1* and *3* to close the *plugging contactor*. The contactor supplies power to the motor with two lines

reversed to quickly stop and reverse the motor. When the motor stops and reverses for a fraction of a turn, the friction wheel pushes back the lever arm to open contacts *1* and *3* to disconnect the motor.

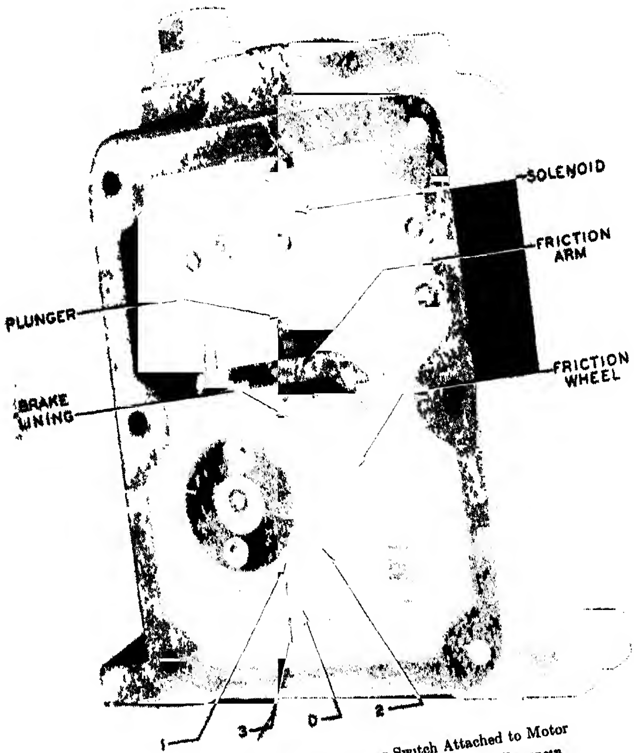


Fig 7 Interior View of Plugging Switch Attached to Motor
Courtesy of Allen-Bradley Company Milwaukee Wisconsin

Since there are two sets of contacts, *1–2* and *2–3*, on the plugging switch, and the friction arm can move in either direction, the switch can plug the motor in either direction. It will also provide plugging for both directions, but in that case two control relays must be used with the reversing switch.

DUPLEX PILOT CONTROL PANEL. A duplex pilot-control panel is a controlling device which alternates the operation of two

starters and motors to divide the burden of service and to insure continuity of service. The control panel is most commonly used for controlling water and compressor pump motors on water and air-conditioning systems.

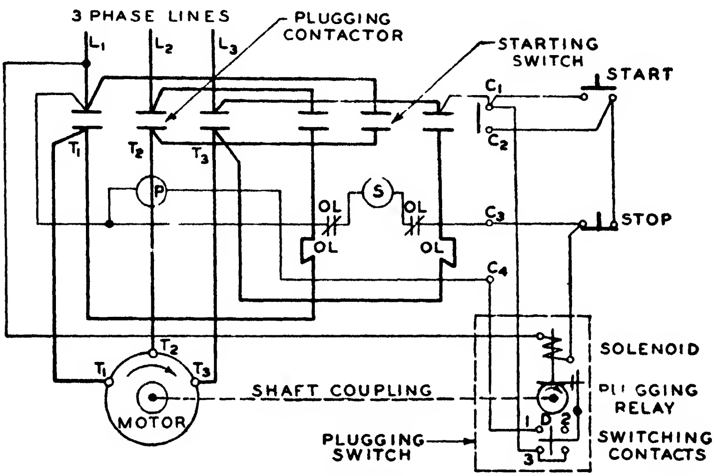


Fig. 8. Schematic Diagram of Reversing Switch and Plugging Relay

For many pump applications, two small motors are used instead of one large motor to provide more flexible and dependable operation for a varying seasonal or daily demand, or anticipated increase in demand at a future date. For example, a pump application may presently require a varying demand of 15 to 50 h.p. with an average normal demand of 25 h.p. and later may require as much as 60 h.p. In this case it would be advisable to use two 30 h.p. motors instead of one 60 h.p. motor so as to have a *standby* unit in case of trouble. A 30 h.p. pump would operate intermittently to supply a 15 or 20 h.p. demand and for prolonged periods under such a condition the service on the two motors can be alternated for alternate periods of load and rest. In case of trouble with one unit the other can be operated continuously or intermittently, as required, while the idle unit is being repaired.

Construction. For this type of installation, dual equipment—that is, two pumps, two motors, two starters, and two disconnect switches —is used with the control panel and auxiliary pilot-control devices.

The panel consists of an assembly of three control relays and a pair of control fuses as shown in Fig. 9. A schematic diagram of connections is illustrated in Fig. 10, in which the *control fuses* and control relays *1CR, 2CR,* and *3CR* constitute the duplex panel. The control devices *1* and *2* may be pressure switches, thermostats, float switches, or other two-wire control devices. For the sake of clarity in explaining the operation of the panel, it will now be assumed that float switches are used and that they operate to keep a storage tank full of water. The *selector switch* is used to provide flexibility of operation in a manner which will be explained.

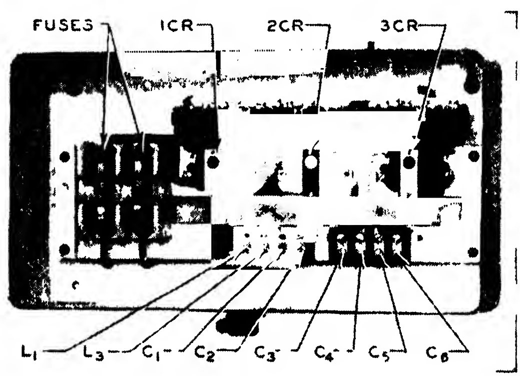


Fig. 9. Duplex Pilot-Control Panel for Alternating Operation of Two Motors

Courtesy of Allen-Bradley Company, Milwaukee, Wisconsin

Operation. It should be remembered that when current flows through and operates the coil of one of the relays, the coil operates all its contacts, closing all those which are normally open and opening all those which are normally closed. For example: In Fig. 10, when the coil *3CR* operates, it operates all contacts marked *3CR*. Then the normally open contacts *3CR* between *19* and *20* are closed; the normally closed contacts *3CR* between *15* and *16* are opened; and so on. The operation of the duplex panel is as follows: When both motors are to be placed in service for alternate and/or simultaneous operation, the two *disconnect switches* are closed and the *selector switch* lever is placed in the position marked *1&2*. The cams of the selector switch close the contacts between *2* and *3*, and *6* and *7*. When the water level in the tank reaches the low limit of float switch, *device 1*, the

switch will connect *3CR* coil across the lines through normally closed contacts *2CR* and *1CR* between *19* and *16*. Then current flows through relay coil *3CR* and causes it to perform four operations. First, relay *3CR* maintains its coil circuit over normally open contacts *3CR*, located between points *19* and *20;* second, relay *3CR* closes starter *1* over circuit *1–2–3–4;* third, relay *3CR* opens the *1CR* coil circuit by opening the normally closed contactor *3CR* between points *15* and *16;* and fourth, this relay *3CR* closes *2CR* coil circuit over *9–10–11–12*. If the load demand increases to the extent that the level continues to drop to the low-level limit of float switch *2*, then *device 2* will close starter *2* over circuit *5–6–7 4* and the two motors will operate simultaneously.

When the demand decreases and level rises to the upper limit of float switch *2*, then *device 2* will disconnect starter *2* to leave only starter *1* in service. Next, if the demand continues to decrease to permit the water level to rise to the upper limit of float switch *1*, then it will disconnect starter *1* and both motors will be idle, or shut down.

However, control relay *2CR* remains closed over its normally open contacts in circuit *9–10–11–12*. Its remaining contacts, between *19* and *20*, lock out coil *3CR* circuit and establish the circuit for coil *1CR* between *14* and *15* for the next operation.

When the water level lowers enough to reclose float switch *1* it will energize coil *1CR*. When relay *1CR* closes, its *1CR* contacts close starter *2* over *5–6–7–8*, open *2CR* coil circuit between *11* and *12*, and lock out coil *3CR* by opening the circuit between *20* and *16*. If float switch *2* closes it will connect starter *1* over circuit *1–2–3–8* for simultaneous operation. In order to insure the closing of *1CR* coil before *2CR* coil opens, relay *1CR* is equipped with *overlapping contacts* as indicated on the diagram. When float switch *2* opens, it disconnects starter *1* and when float switch *1* opens it disconnects starter *2* and all the control relays in readiness for the next cycle of operation, which is a repetition of the one first described.

Disconnecting Starters. If it is desired to disconnect both starters, the two disconnect switches must be opened and the selector switch placed in the *off* position. This leaves both starters completely *dead* for servicing.

When it is desired to disconnect starter *2* for servicing or for other reasons, its disconnect switch is opened and selector switch is

placed in position *1* to close the contacts between *2* and *3*, and *2* and *7* to permit starter *1* to operate whenever float switch *1*, or both *1* and *2*, are closed. The power and control circuits of starter *2* are entirely disconnected for servicing. If starter *1* is disconnected, selector switch is placed in position *2* to allow starter *2* to operate whenever either or both float switches are closed.

This duplex panel can be used with any standard type of automatic starter on any type of duplex motor application which is to operate in a manner similar to that described.

AUTOMATIC INTERLOCKING CONTROL

SPECIAL MACHINE APPLICATIONS. The remarkable progress during recent years in mass production of all kinds of products and machines is due to the rapid development of automatic machines and machine tools, which perform a multiplicity of operations automatically and at high rates of speed.

Some machines which are designed to perform automatically a relatively few operations may require only one, two, or three motors. Others which must perform many and more intricate operations, may require anywhere from a few to fifty or more motors with various speed and torque characteristics, controlled so as to operate in proper time and mechanical sequence, to produce an uninterrupted flow of finished products. The successful operation of these machines depends on reliable motors and control. The motors employed for various operations may be any of the different standard types that are available, squirrel-cage, slip ring, or multispeed. The automatic interlocking control for all the motors may consist of any number of different types of devices such as starting switches, accelerating contactors, reversing switches, resistors, control relays, timing relays, pressure controls, temperature controls, time clocks, motor-driven timing relays, limit switches, plugging relays, push buttons, and others too numerous to mention.

Since automatic machines perform many operations by means of intricate mechanical motions and electrical functions, it naturally follows that the control for the motors on these machines is rather complex in structure and operation. The mechanical motions of the driven machine may be produced electrically, hydraulically, or by a combination of the two, and all functions must be correlated so as to

produce the operations which the machine must perform. For example, the rotation of an electric motor will produce a mechanical motion which in turn will operate an electrical pilot device, such as a limit switch, to actuate a magnetic switch that starts another motor. This second motor may start an oil pump which, by means of hy-

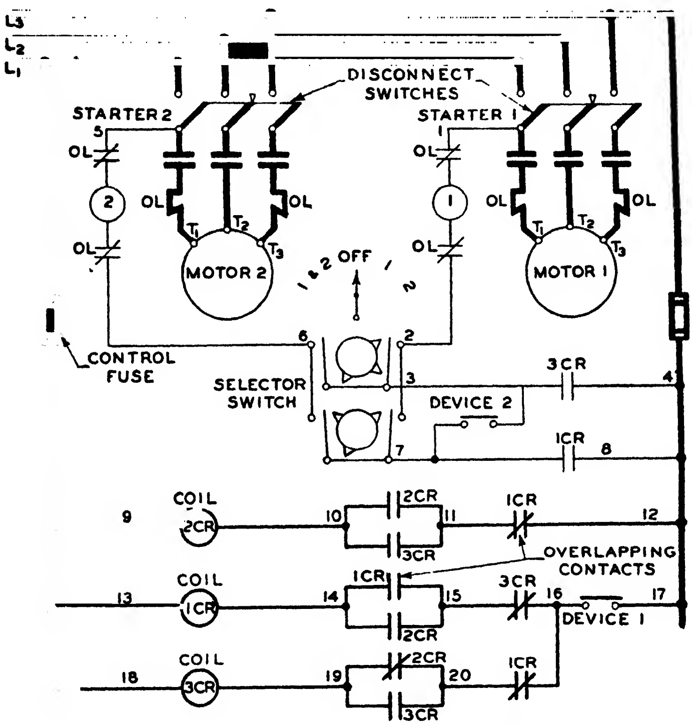


Fig. 10. Schematic Diagram of Connections for Two Starters Controlled by Duplex Pilot-Control Panel

draulic pressure, will close a pressure switch that closes another starting switch to connect another motor, and so on. All of the motions and functions must be mechanically and electrically interlocked so as to perform the machine operations in proper order.

Electrical power can be directly translated into two kinds of motions—straight-line and rotary. The straight-line motion can be produced to a limited degree by means of a solenoid. The limited motions can be amplified by a system of linkages or levers to operate

such devices as valves, clutches, brakes; locking, indexing and positioning mechanisms, and other devices requiring limited power and motion. Other straight-line motions may be produced hydraulically, or by converting rotary motions produced by electric motors.

Rotary motions of the slow-speed type can be produced mechanically or hydraulically by means of a rack and pinion, rachet wheel, or similar devices. High-speed motions are produced by motors. The motions may vary with respect to speed, torque, and number of revolutions. Each high-speed motion must be carefully analyzed for determining the type of motor which will provide the proper characteristics. Rotary motions which are produced entirely by means of electric power are saws, grinders, and drilling, tapping, boring, and milling machines, and so on. These machines are usually driven by motors, and the number of motors employed is determined by the number of motions to be produced, and the relationship between initial and operating cost of the equipment and the rate of production.

Because of the complexity of the problems encountered in the field of machine applications and operations, it is essential that the designer of the machine possess some knowledge of electrical control. Likewise, the designer of the control should possess some knowledge of the machine and its operations. Then the two can understand each other's problems in working out control which will perform accurately, dependably, and efficiently. After the method of driving the machine and producing the various motions have been determined, it is necessary to determine the best method of producing the motions. It is then necessary to decide upon the interlocking arrangement and kind of control to produce the motions in proper order.

Selecting Control. Some of the essential questions to be considered in selecting the control equipment are: (1) What means will be employed to start the machine—manual or automatic--and will it be started, initially, with or without the load connected? (2) Can across-the-line starting be used, or is it necessary to employ reduced-voltage starting to prevent shock or excessive strain on the machine or the work being processed? (3) Does the load consist of friction, inertia, or a combination of the two? (4) Will the machine be stopped manually or automatically, and will it be allowed to coast to a stop or must it be stopped quickly with a plugging or zero-speed switch? (5) Is it necessary to employ magnetic brakes for stopping and hold-

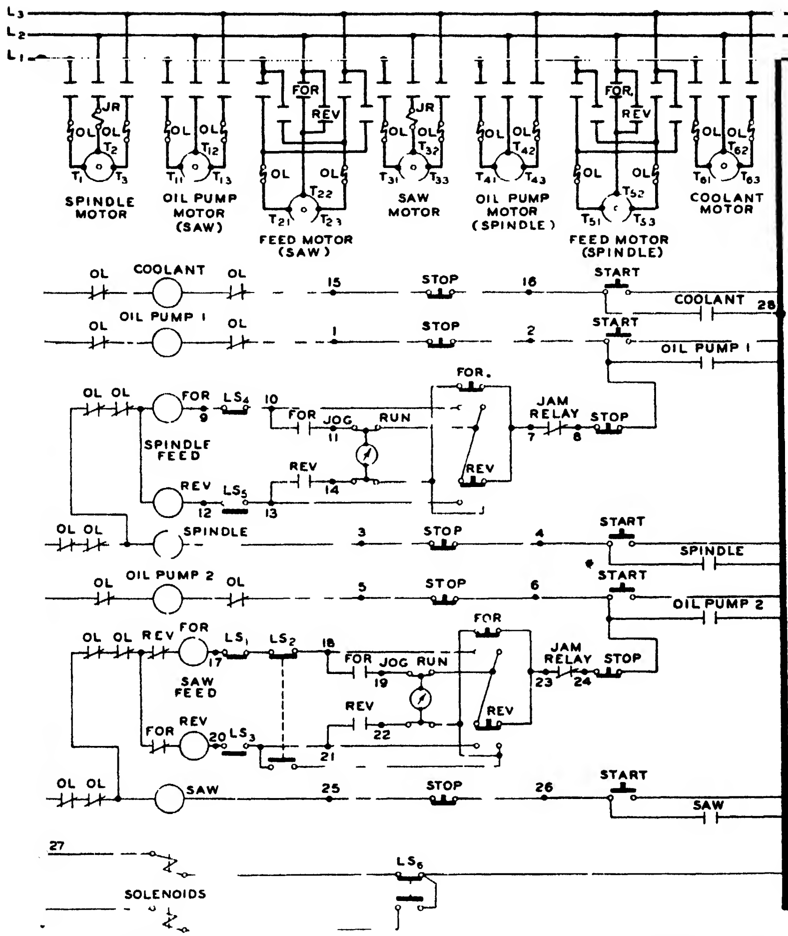


Fig. 11. Elementary or Line Diagram for Control Panel on Seven-Motor Spar Milling Machine

ing the machine or some part of it in a definite position for a certain length of time? (6) Are indexing operations required between various operations for entering and removing the work being processed? (7) Is setting up or inching, reversing, or speed regulating required, to what degree and during which cycle or cycles of operation? (8) Are timing cycles or motion limits necessary, and to what degree of accuracy?

Other essential considerations in designing the control are safety for operator, machine, control, and motors. These involve *no-voltage*

protection against accidental starting of the machine following restoration of power after a power failure; protection against faulty operation; overload protection for the motor, and overtravel protection for limited motions of the machine.

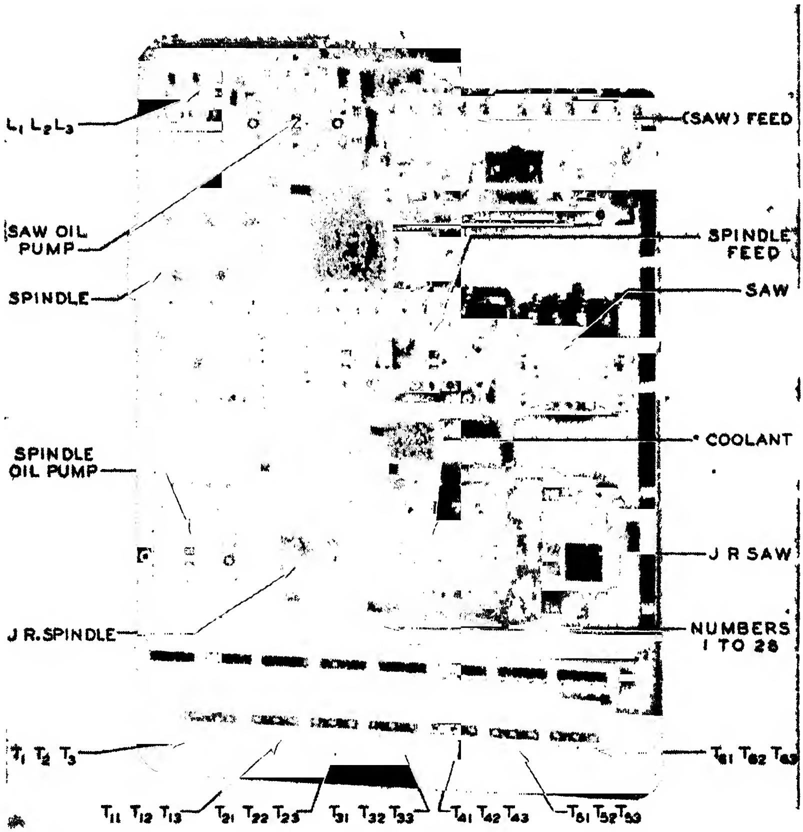


Fig 12 Control Panel for Seven-Motor Spar Milling Machine
Courtesy of Allen-Bradley Company Milwaukee, Wisconsin

Design Procedure. With all the preceding information at hand, the control designer proceeds with the construction of a line diagram similar to the one shown in Fig. 11 to determine the kind and number of devices and the manner of wiring and interlocking. After the line diagram is completed and carefully checked, the designer writes the specifications for the materials and devices so that the draftsman or

layout man can lay out a properly arranged and well-constructed composite control panel. Working drawings and a complete wiring diagram are then made and turned over to the production department for construction and wiring. When finally completed, the composite control panel appears as shown in Fig. 12. This control panel was designed for controlling the seven motors mounted and used on a milling machine designed for making the wing spars for airplanes. A line diagram of the panel is shown in Fig. 11.

You will notice that the wiring shown in Fig. 12 is arranged neatly and toward the back part of the panel. The alternating-current supply lines are at the top on the left, and the starter switch for the largest motor is mounted directly below it. The motor terminals for the largest motor are at the lower extreme left on the panel and are marked T_1, T_2, T_3, for the spindle motor. The other motor terminals are marked on the bottom terminals strip, T_{11}, T_{12}, T_{13}, for the next, T_{21}, T_{22}, and T_{23}, and so on, up to the last right-hand terminal board, which is marked T_{61}, T_{62}, T_{63}. These numbers on the controller terminals correspond with the numbers indicated on the motors, Fig. 11, and in the wiring diagram Fig. 13.

The control strip terminals are arranged as shown in Fig. 12, and are numbered *1* at the left to *28* at the right. The three right-hand terminals each are marked *28* in order to provide three terminals to which the returned circuit from the push-button stations can be attached without placing several wires on the same terminals. This provides convenient connection since there are several push-button stations, Fig. 13, each of which must have a wire *28* going to it. The wiring of the switches, Fig. 12, is shown in detail in the wiring diagram in Fig. 13. The heavy lines indicate the main circuits through to the motors, and the lighter weight lines indicate the control circuits from the push buttons to the controllers or starting switches.

It will be seen by referring to Fig. 11 that five of the seven motors can be started in any order desired by simply pressing the starting button. However, the *feed motor* on the *saw* and the feed motor on the *spindle* cannot be started until *oil pump 2* and *oil pump 1* have been started. This is shown in Fig. 11 by the contactors marked *oil pump 2* and *oil pump 1*. This contact in addition to holding the oil-pump contactor closed also provides a circuit through the *jog* push button and the *run* push button on those push-button control sta-

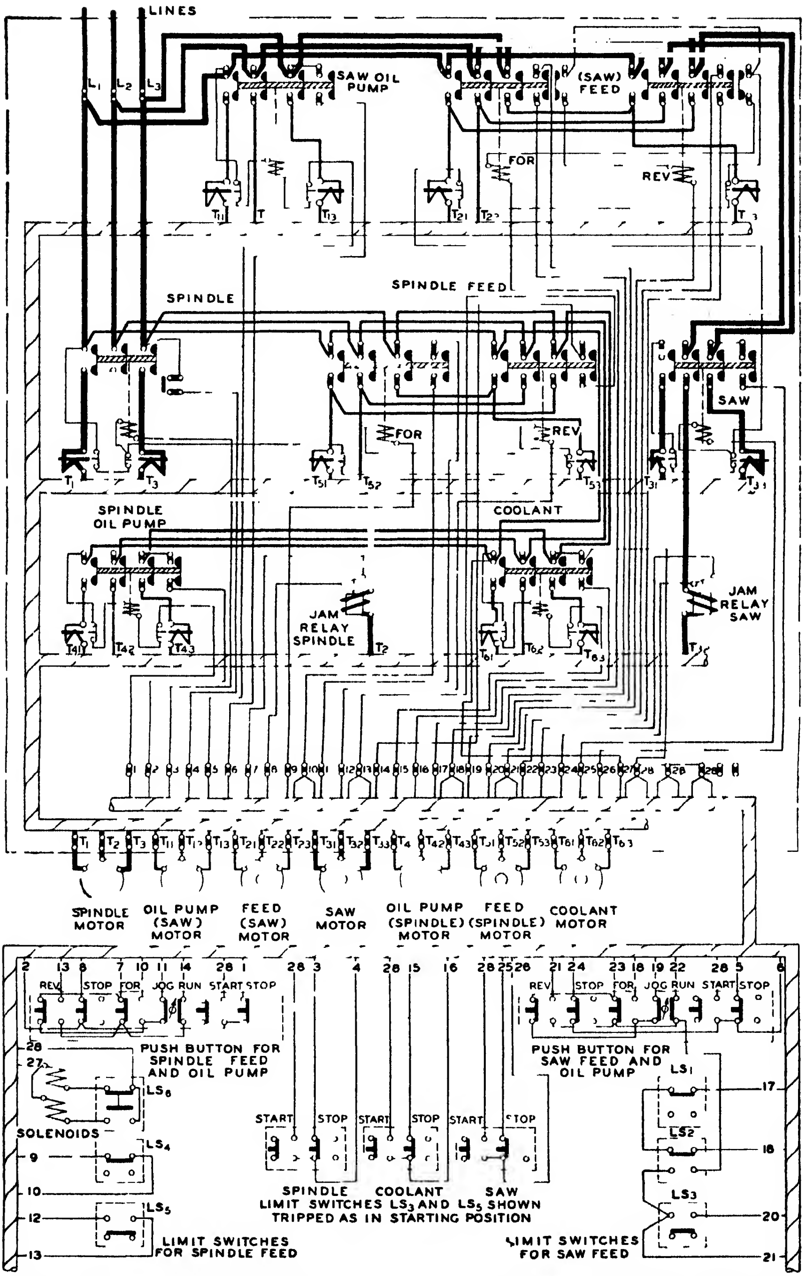


Fig. 13. Connection Wiring Diagram of Control Panel for Seven-Motor Spar Milling Machine

tions, Fig. 13. The feed motors on the spindle and the feed motors on the saw are stopped by *jam relays*. These relays are operated by the main current of the middle phase to the spindle and saw motors passing through the relay windings. When the current exceeds the setting of the *jam relays* it opens the circuits of the *feed motors*, thus slowing

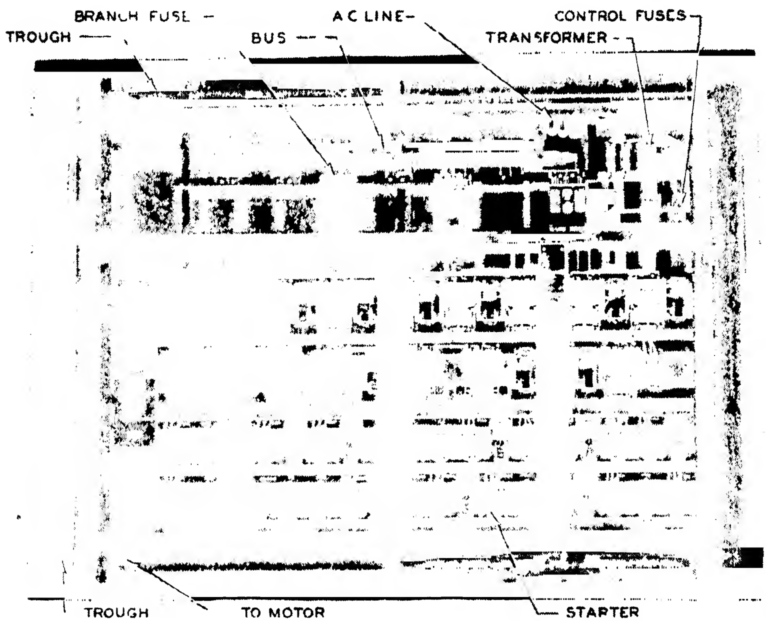


Fig. 14. Control Panel Designed for Controlling Forty-Three Motors on Large Foundry Sand Conveyor System

Courtesy of Allen Bradley Company, Milwaukee, Wisconsin

down the feed motors until the overload on the saw or spindle has been removed.

CONTROL PANEL FOR 43 MOTORS. The control panel shown in Fig. 14 was designed for controlling 43 motors of various sizes used for operating a large conveyor system in a foundry. The main *alternating-current supply* comes into the three lugs on the end of the *bus* at the right. Connection to the switches for the different motors are made through the *branch circuit fuse box* and disconnect switch, three of which are shown in position. Provision is made for mounting four more branch circuit fuses and disconnecting switches,

directly below the bus. A *transformer* at the upper right-hand corner of the panel supplies current for operating the control circuits. The control circuits are protected by the *control fuses*. A large deep wiring *trough* is provided for making a connection and bending the cables into the conduit. This will be attached to the end top and bottom of the control panel The control wiring for the push buttons is placed adjacent to the three main *motor terminals*. Each of the *starting*

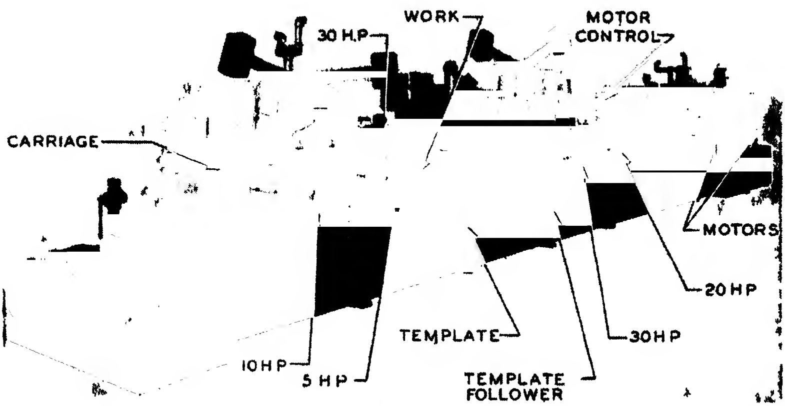


Fig 15 Large Airplane Spar Milling Machine Operated by Seventeen Motors
Courtesy of Farnham Manufacturing Company Buffalo New York

switches and the motor controller are assembled with the same designation or number as is given to that motor in the foundry.

Control for Milling Machine. Another much larger spar milling machine operated by seventeen motors is shown in Fig. 15. This machine is designed and built to machine completely, in one setting, a spar cap of the inner wing of a twin-engine airplane bomber. The machine consists of a 30-foot bed upon which ride three independently fed *carriages*. The heads of the center carriage are equipped with two *30-h.p.* motors and one *20-h.p.* motor; each of the two end carriages is equipped with one *10-h.p.* and one *5-h.p.* motor. All operations are performed simultaneously under a flood of coolant supplied by two 300-g.p.m. pumps driven by two 5-h.p. motors. The center head is equipped with a 3-h.p. two-speed horizontal feed motor; and each of the two end heads is equipped with a 1½-h.p. two-speed horizontal

feed motor and a ¼-h.p. vertical feed motor. In addition each one of the heads is equipped with a ⅛-h.p. oil-pump motor.

The seven motors on the three heads which drive the multiple-spindle cutting tools can remove a total of 220 cubic inches of dural metal per minute and complete a spar in 15 to 20 minutes. By

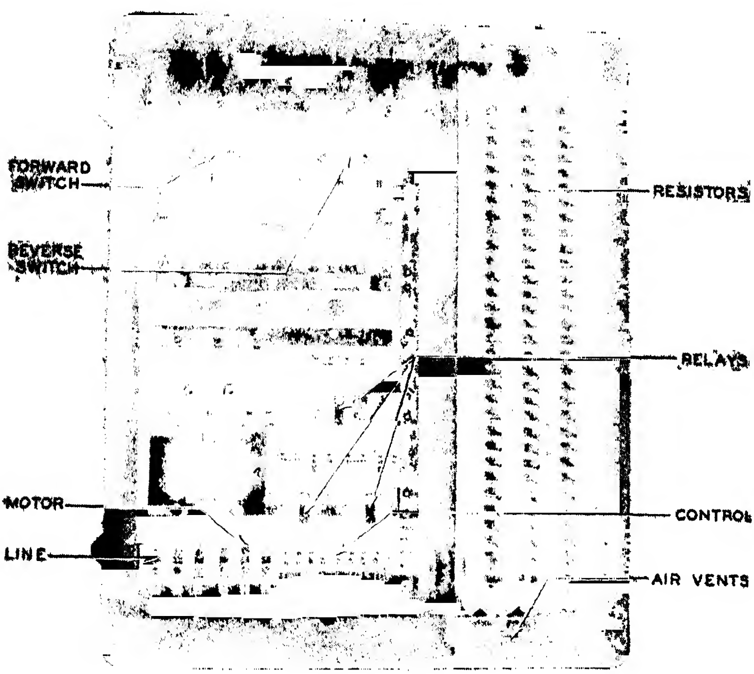


Fig. 16. Reversing Control Panel for Lathe Motor Using Full-Voltage Starting and Reduced-Voltage Plugging
Courtesy of Allen-Bradley Company, Milwaukee, Wisconsin

methods used prior to the design and construction of this machine, it required 60 hours to make the same type of spar. This means that the machine can produce from 180 to 240 spars in the time required to produce one spar by the old method.

Control for Lathe. Another type of control panel is shown in Fig. 16. This panel is designed for controlling the *motor* on a lathe. It provides full voltage for starting and reduced voltage for plugging for quick stopping. The *resistors* at the right are introduced when the

motor is reversed, so as to reduce the degree of plugging and prevent undue strain on the driven machine and the work. The stopping time, which is determined by the magnitude of plugging current, can be adjusted by changing the connections on the resistors. The plugging relay (not shown) is a separate device which is directly connected to the shaft of the motor or machine.

Control Station Devices. Some of the various types of push-button control stations used with automatic control are shown in Fig. 17. These types vary with respect to contact arrangements, interlocking, style, and enclosures.

Fig 17 Exteriors of Different Styles of Control Stations
Courtesy of Allen-Bradley Company Milwaukee Wisconsin

In Fig. 17, Nos. 1, 2, 10, 12, and 20 have 3-button stations marked *Forward*, *Reverse*, and *Stop* used to start, stop, and reverse direction of rotation of motor. No. 3 is a wall-switch type of start-and-stop station, usually mounted in the wall. It is often provided with a pilot light to indicate when the motor or device is operating. No. 4, water-tight, operated by thumb lever having *On* and *Off* stations. Nos. 5, 8, and 9 are start-and-stop 2-button stations. Internal view is shown in Fig. 18. No. 6 is a stop-button station. No. 7 is a two-position selector switch operated by turning the pointer knob. The positions are marked *Auto.* (Automatic) and *Hand.* A three-position switch marked *Auto.*, *Off*, and *Hand* is shown at No. 13. No. 11 is a start-button station. Nos. 14 and 15 are two-button stations provided with a stop-locking bar (bottom) which can be used for locking the stop circuit open. Nos. 17 and 18 are two-button stations used in hazardous gas or dust locations, such as refineries, distilleries, flour mills, and so on. Nos. 19 and 20 are 2- and 3-button stations with cast-iron covers where operating conditions are severe.

The *contacts* may be normally open, *Start* button, Fig. 18, or normally closed, *Stop* button, Fig. 18, or combinations of both. They may be momentary opening or closing, or maintained so as to remain in the position placed until released by the operator. For many applications they are equipped with interlocking circuits, indicating lamps, multiple circuit contacts or combinations of these features. With respect to style they can be furnished for surface mounting, flush mounting in walls, flush mounting in cavities of machines or flush mounting on panels. Enclosures of various types are available

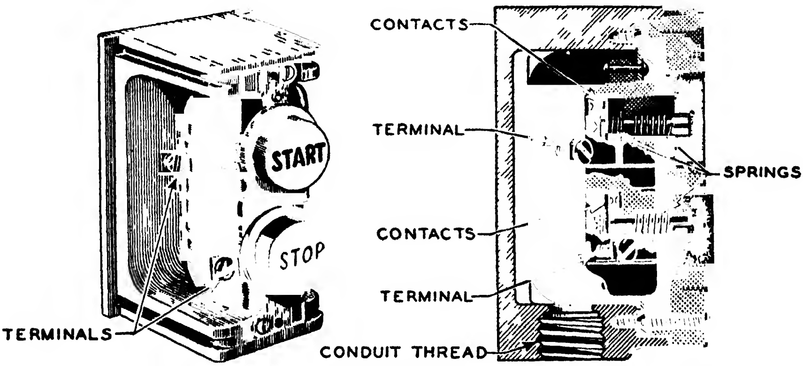


Fig. 18. Interior and Cross-Sectional View of a Start-Stop Push-Button Station

for protecting the mechanism from all kinds of surrounding conditions such as dust, moisture, or acid-laden atmosphere.

Push-Button Panels. The push-button control panel in Fig. 19 is a special assembly equipped with indicating lamps, designed for a control panel used on a large conveyor system having 15 motors. It consists of a pilot light below the name plate, a start button (dark) and a stop button (light color).

Various types of pilot control devices are shown in Fig. 20. The limit switches may be generally classified with respect to operation as push type, roller type, fork type, track type, and gear-driven type. Most of these types can again be classified with respect to motion as slow action and snap action. The slow-action types are used when the actuating mechanism travels with sufficient speed and overtravel to insure positive operation. The snap-action types are more commonly used because they are suitable for practically all applications.

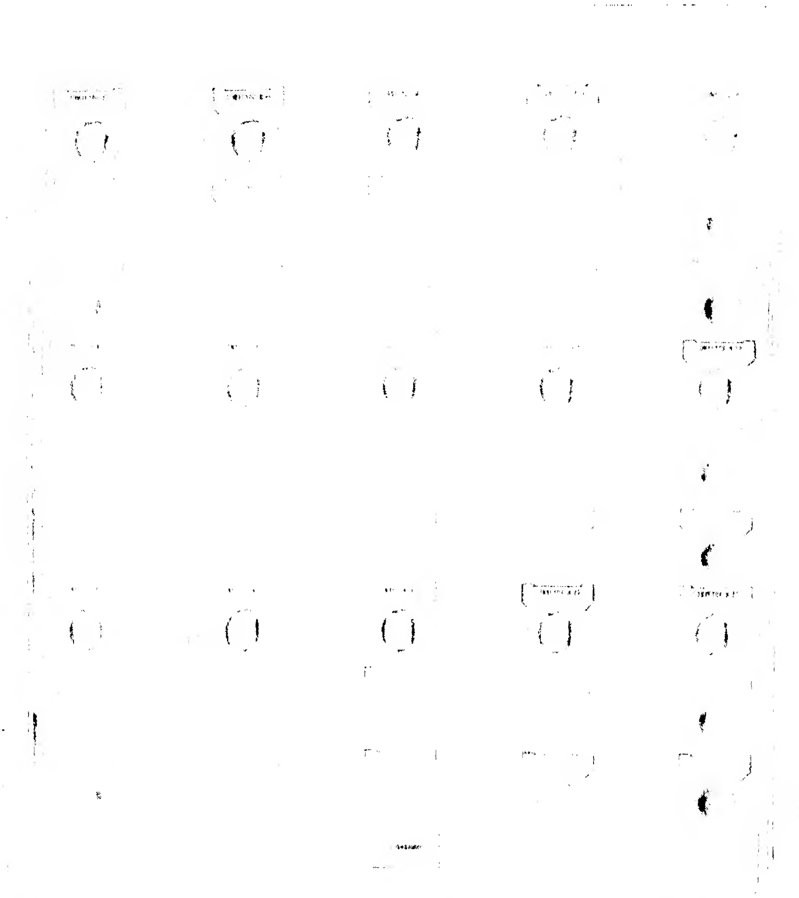


Fig. 19. Push-Button Panel with Indicating Lamps Used to Start and Stop Fifteen Motors on a Conveyor System

Courtesy of Allen-Bradley Company, Milwaukee, Wisconsin

They are somewhat costlier than the slow-action types but are more dependable for positive operation. The units marked *1*, *2*, and *3* are fully enclosed lever-operated limit switches. The units marked *4* and *6* are gear-driven limit switches which can be set for any number of revolutions of the motor or driven machine. Unit *7* is a plugging switch and unit *8* is a zero-speed switch.

The control panels, control stations, and pilot devices shown and described in this section wiii give the reader some idea of the intricacies of automatic interlocking control. Almost every special-

machine application requires tailor-made control and the control devices necessary to perform the innumerable operations are almost unlimited.

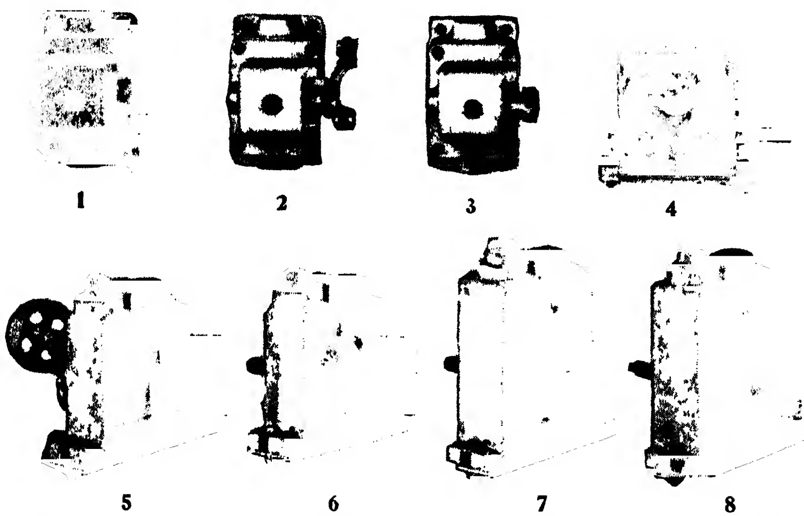


Fig 20. Exterior View of Lever-Operated Limit Switches and Interior Views of Plugging Relays
Courtesy of Allen-Bradley Company Milwaukee, Wisconsin

INSTALLATION, INSPECTION, AND MAINTENANCE OF CONTROL

The importance of proper installation and periodic inspection and servicing of control equipment cannot be too strongly emphasized. Because of the severe demands placed on mechanical and electrical equipment, it naturally follows that trouble or failure is bound to occur sooner or later, even though the equipment is designed and built to conform with the highest degree of engineering standards. Machines, like men, become fatigued and eventually fail, but the life of both may be prolonged if properly cared for.

INSTALLATION. The location and installation of control equipment must be given careful consideration. These factors should be considered from the point of accessibility, temperature, surrounding hazards, atmospheric conditions, and protection against mechanical injury. The control should not be installed near boilers, radiators, furnaces, steam pipes, plating tanks, or in dust, moisture, or gas-laden atmosphere. It should be protected from mechanical injury which

might be caused by trucks, cranes, conveyors, or other material-handling equipment. It should also be protected from the splashing of water, oil, and other harmful liquids which will interfere with operation of the control. If it is impossible to avoid hazards by selection of location, the control should be incased in the proper type of protective enclosure, such as dust-tight, watertight, oil-immersed, or explosion-proof.

If after the installation has been completed it is found that the equipment does not function properly, the trouble may be due to one or more of the following reasons: (1) The motor may be incorrectly connected to the control. To find the trouble the connections should be checked with the diagram which accompanies the control. (2) The motor may be overloaded because the size selected is too small. To investigate this possibility the current should be measured with an ammeter while the motor is operating with maximum load and if the current is found to be too high the load must be reduced or a larger motor and controller must be installed. (3) The voltage at the motor terminals may be too low because of overloaded power lines. This will cause the control to operate unsatisfactorily or to cause the motor to overheat. To discover this condition, the voltage should be measured with a voltmeter while starting the motor and also when the motor is running at full speed. If the voltage is low it must be remedied by reducing the operating load on the power lines, or by installing more copper to carry the load and thus reduce line-voltage drop. (4) The horsepower rating of the controller may not be the same as the rating of the motor, or the voltage and frequency of the control, motor and power lines may not be in agreement. In that case steps must be taken to correct the discrepancies. (5) If the motor has been operating, stops, fails to start, fails to stop, or does not perform properly when the control is operated, it may be caused by defective power or control connections or wiring. The power connections between control and motor should be checked with the connection diagram and all power terminals on motor, and controller and pilot-control terminals on controller should be checked for firm and rigid connections. Loose connections produce a high-contact resistance which in turn produces a high-voltage drop across the loose contacts and reduces the voltage where it is essential for satisfactory performance of the equipment.

PERIODIC INSPECTION AND MAINTENANCE. After the equipment is made to operate satisfactorily it is essential that the complete installation be periodically inspected according to a planned schedule. The frequency of inspection is largely determined by the severity of the service on the equipment. In some cases once every month may be sufficient, whereas in other cases once every two weeks, once every week, or even once every few days may be necessary.

Since it may be expected that sooner or later trouble will occur, the inspector or service man should familiarize himself with the equipment under his care. Knowledge of the principal causes of trouble will help him to adopt appropriate measures to prevent such causes. Some of the common causes of trouble, their remedies and preventive measures, are explained on the following pages.

Dust. Dirt, moisture, and all kinds of dust are detrimental to satisfactory performance of control and motors and should be removed as often as necessary. In dusty locations dust-tight equipment should be used and in a moist or damp atmosphere it is advisable to use watertight equipment.

Cleaning Contacts. Oxidation and corrosion greatly interfere with the operation of contacts and moving parts. Copper oxide is a nonconductor of electricity and when copper contacts are oxidized they will make poor contact for conducting current, or if badly oxidized will even prevent any current from flowing. Such *copper* or *brass contacts* must be frequently dressed with a file or cleaned with sandpaper. The contacts need not be absolutely smooth for satisfactory operation. Contact trouble caused by oxidation may be avoided by using contacts made of silver alloy, because silver oxide is a conductor of electricity. Contacts made of *silver do not require dressing* and manufacturers of controls with this type of contact caution against dressing because it reduces contact life by destroying valuable contact material. Replacement of silver contacts is made only when all of the silver alloy is worn away.

Corrosive Vapors. Chemical fumes and acids increase the rate of oxidation and corrosion and where these elements are present it is advisable to use oil-immersed equipment. If the fumes are explosive it is necessary either to use explosion-proof enclosures or to install the control remote from the adverse atmospheric conditions.

Oiling. To prevent corrosion of bearings and other close-fitting moving parts it is necessary to oil such parts frequently, but sparingly, with light oil. Grease or too much oil causes an accumulation of dust which interferes with operation.

Voltage. Abnormally low voltage will cause the entire installation to perform improperly. Standard coils on control equipment are designed to operate at 85 per cent of normal rated voltage and trouble is sure to occur if it falls below this value. The voltage condition must be corrected by voltage regulating or boosting equipment or, if the lines are overloaded, additional copper must be installed to carry the load. Excessively high voltage will overheat and damage or burn out coils. Standard coils are designed to withstand 110 per cent of normal rated voltage. High voltage should be corrected by the supplier of the power.

Magnet Cores. Sluggish operation of contactors may eventually cause complete failure of operation. In a complex control panel the unsatisfactory operation or failure of one small contactor will cause the entire installation to become inoperative. The bearings of all contactors should be frequently checked for free operation, and the magnet poles inspected for dirt, rust, or any foreign matter between the pole faces, which may prevent the contactor from closing properly. Besides interfering with the operation of the contactor, obstructions between the pole faces may maintain an *open* in the magnetic circuit and cause the magnet coil to burn out. Therefore, the inspection of magnets is highly important. Dirt or other foreign matter found in the magnetic circuit should be removed with a cloth and cleaning solvent, but the pole faces must not be filed because they are ground to a high degree of accuracy to produce a perfectly close fit when the magnet is closed.

Shading Coils. Shading coils are used to produce steady pull and quiet operation of A.C. magnets, and usually consist of one turn of copper wire or bus imbedded in the armature or base of the magnet. When a shading coil is broken, it becomes useless and the contactor will chatter very noisily. The same noise in a lesser degree is produced by dirt between the pole faces. If a broken shading coil is found it must be replaced.

The construction of a *shading coil* is illustrated in Fig. 21 which shows the *plunger* and part of the laminated *magnetic-core* around the

coil. The direction of the magnetic lines of force through the core and plunger is shown by long arrows. These are produced by the *contactor coil.* With alternating-current flowing through the contactor coil, the lines of force will change as the direction of current-flow changes in that coil. When the current decreases to zero and changes its direction of flow in the contactor coil, the magnetism or lines of force (shown by the long arrows) will also decrease to zero. When the lines of force are zero, there is a tendency for the plunger to drop away from the core. Then as the magnetic lines of force increase in

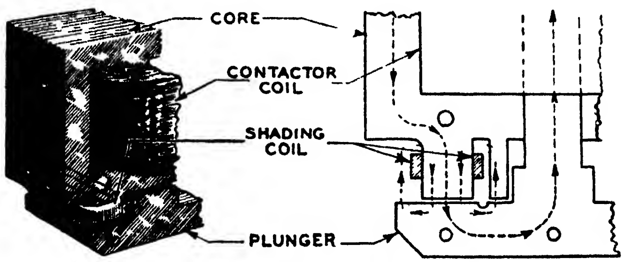


Fig 21 Left, Location of Shading Coil in Magnet Right Diagram of Magnetic Lines of Force in Shading Coil, Contactor Coil, and Plunger

the opposite direction, the plunger is pulled back tight against the core. This occurs 120 times in a second in a 60-cycle alternating-current circuit, and produces quite a chatter of the plunger.

In order to reduce this chatter, a copper or brass ring called a *shading coil* is placed in the *core* as shown in Fig. 21. This coil operates on the principle of a transformer which has a short-circuited secondary winding.

When the magnetic lines of force are decreasing to zero, a voltage is produced in the shading coil. Since the ring is short, of low resistance, and a complete electrical circuit is formed, a current flows around through this ring. This electric current flowing through the ring produces a magnetic field around the ring as shown by the dotted lines and arrows. This magnetism produced by the shading coil is greatest when lines of force produced by the contactor coil are decreasing to zero. These lines of force through the core and plunger are shown by long arrows, Fig. 21. Thus the magnetism of the shading coil will tend to hold the plunger and core together and prevent the plunger from dropping down. Since this magnetism occurs when

the magnetism from the contactor coil is zero, there is always some magnetism between the core and plunger to hold those two iron pieces together.

An open circuit (a break) in the shading coil will not allow any current to flow through it because its circuit is not complete. Hence the lines of force shown about the shading coil in Fig. 21 will not be produced, and the plunger will chatter against the core.

Poor Contacts. Loss of pressure on contacts caused by heating of springs or badly worn or burned contacts may be the cause of serious trouble. Loose contacts cause high resistance with resulting high voltage drop and high temperature. If allowed to operate with improper pressure the temperature may become high and cause welding which prevents parting of the contacts when the coil is de-energized. A rebounding of the contacts due to improper relation of springs and magnet parts may cause the same trouble. When contacts open momentarily during the closing motion an arc is created. This causes small particles of the contact material to melt and weld the contacts when they reclose after the rebound. In either case the welded condition will not be discovered until an attempt is made to stop the motor. Then it is found impossible to stop the motor because of the failure of the contactor to open and interrupt the power. Welding causes a serious situation because the machine will not stop when it should. Such a situation may cause damage to the work, the motor, the driven machine, or serious injury to the operator.

Therefore, contacts should be inspected frequently for pressure, and contactors should be observed for indications of rebounding. Faulty springs, worn or burned contacts, and any other worn parts should be replaced and the contactor should be adjusted to restore satisfactory operation. The use of control with silver alloy contacts will materially reduce the possibility of welding.

Loose Connections. Loose connections on the control or motor, caused by vibration or by expansion and contraction produced by changing temperature are another common source of trouble. They cause rising temperature, increased resistance, and high-voltage drop. An increasing resistance causes a still higher temperature with correspondingly higher-voltage drop. This action is cumulative and may cause a condition approaching an open circuit. All push buttons, limit switches, pilot devices, and all power contactors and motors

should be inspected for loose connections and worn or loose contacts. Loose connections must be made secure and worn parts should be replaced. Vibration may be reduced by placing rubber, cork, or felt between the control and its mounting base.

Friction between moving parts, sticking of magnets, and mechanical interference of motions and devices may be caused by misalignment of parts. These conditions must be corrected by making proper adjustments.

Ordinary use causes parts to become worn, some wearing out faster than others. These parts and others which are vital to the operation of the control should be checked frequently and replaced when they show signs of excessive wear.

An open or burned-out coil will interfere with the performance of the control and may cause it to become entirely inoperative. If the magnet can be closed by hand but not with normal voltage applied directly to the coil terminals it is a sure indication that the coil is open and must be replaced.

Relays. Frequent tripping of overload relays causes undesirable and annoying interruptions in the operation of machines. This may be due to a defective relay, but in most cases it is caused by sustained overloads on the motor. Overload relays perform the important function of protecting the motor and frequent tripping should be a warning to the operator and inspector to make a thorough investigation of the cause of tripping. Overload relays of the resistance thermal type should be allowed to cool and permit the solder to solidify before attempting to reset after the relay has tripped. Premature resetting may result in damage to the relay. The time required for solder to set is from one to two minutes depending on the operating conditions. Before resuming operation the motor should be checked for free rotation and the overload condition should be removed, if one exists.

Motors. Motors as well as their control may be the cause of trouble and they also should be inspected frequently. They should be oiled at regular intervals and checked for tight bearings and belts, as well as for misaligned gears, couplings, and pulleys. The motor and all moving parts of the load should operate freely. All grease, oil, dust, and dirt should be removed from the windings to prevent electrical failure.

Worn bearings in motors cause a displacement of the rotor and increase the load. If allowed to continue operating under this condition the load current may become so high that the windings will be damaged. Also the displacement of the rotor may result in mechanical injury to the windings.

A broken wire, high resistance connection, or a blown fuse will cause a polyphase motor to operate as a single-phase motor; and unless the motor is properly protected with overload relays, it will overheat and possibly burn out a winding. If a single-phase condition occurs while the motor is running, the motor may continue to run slow if the load is light, or it may stop if the load is heavy. If it continues to run, the single-phase condition can be detected by a distinctive single-phase hum. If detected, the motor should be disconnected to prevent the possibility of damage to the motor windings. The motor may be restarted after the circuit has been restored.

MAINTENANCE OF CONTROL. The informed and experienced service man knows that it is unwise to gamble with obsolete or worn-out equipment. This is especially true in cases where continuity of operation is of vital importance. Using modern and well-kept equipment is the best insurance for avoiding trouble and interruptions in operation.

Spare Parts. To be prepared for emergencies, a complete set of spare parts such as magnet coils, contacts, springs, shading coils, contact supports, and all parts subject to considerable wear is indispensable. One of the curses of emergency repairing is the necessity for making a makeshift part. Making homemade parts may seem economical, but in the end it may prove extremely costly because of unsatisfactory performance or long delays in operation. The manufacturer of the equipment with years of experience has given careful study and much thought to the design, development, and manufacture of every part of the product and can supply spare parts that will be more dependable and economical than homemade parts.

Repair Parts. For standard devices, the manufacturer can usually supply *repair part lists* which show a drawing of the device and lists the various parts and prices. For semistandard and special equipment the manufacturer upon request will furnish drawings

of the devices which constitute the equipment and make up part lists of all the parts involved. In addition, if it is requested, the manufacturer will make recommendations concerning the kind and number of parts that should always be kept on hand to insure uninterrupted service.

Infrequently, troubles of an obscure and baffling nature occur. In such cases it is usually necessary to employ the service of specialists. These men will make exhaustive tests to locate the cause of the trouble and will recommend corrective remedies.

As previously mentioned, the use of high-grade modern equipment is the best insurance for dependable and satisfactory performance. However, the use of good equipment creates a tendency to expect it to function indefinitely without much attention, and the equipment ultimately fails because of the lack of proper care, and is then discredited. The only sound policy is to use the best equipment and give it the best attention by vigilant watchfulness, periodic and careful inspection, and first-class maintenance.

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